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EXECUTIVE SUMMARY

A STUDY OF THE DURABILITY OF BERYLLIUM ROCKET ENGINES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER

CONTRACT NAS9-13476

OCTOBER 1974

ROCKETDYNE DIVISION
ROCKWELL INTERNATIONAL
6633 CANOGA AVENUE
CANOGA PARK, CALIFORNIA 91304

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PREPARED BY

R. D. PASTER
G. C. FRENCH

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER

N. CHAFFEE, TECHNICAL MONITOR

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FOREWORD

This executive summary presents the highlights of a 1-year program (June 1973 - June 1974) entitled "A Study of the Durability of Beryllium Rocket Engines." The contract (NAS9-13476) was conducted by the Rocketdyne Division of Rockwell International, and was administered by the Lyndon B. Johnson Space Center of the National Aeronautics and Space Administration. The NASA Technical Monitor was Mr. N. Chaffee of the Auxiliary Propulsion and Pyrotechnics Branch. The Rocketdyne Prgram Manager was Mr. R. W. Helsel and the Project Engineer was Mr. R. D. Paster.

ABSTRACT

An experimental test program was performed to demonstrate the durability of a beryllium INTEREGEN rocket engine when operating under conditions simulating the Space Shuttle reaction control system. A Vibration Simulator was exposed to the equivalent of 100 missions of X, Y, and Z axes random vibration to demonstrate the integrity of the recently developed injector-to-chamber braze joint. An Off-Limits engine was hot fired under extreme conditions of mixture ratio, chamber pressure, and orifice plugging. A Durability Engine was exposed to six environmental cycles interspersed with hot-fire tests without intermediate cleaning, service, or maintenance.

Results from this program indicate the ability of the beryllium INTEREGEN engine concept to meet the operational requirements of the Space Shuttle reaction control system.

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INTRODUCTION

The broad and aggressive spectrum of activities which has been proposed by NASA for the decade of the 70's and beyond has created the need for a family of propulsion systems and components of increased capability. The currently on-going programs, including the Space Shuttle and planetary probes, as well as potential future programs including Space Tug, Space Station, reusable satellites, deep-space probes, and Mars exploration, without exception, will require reaction control system (RCS) engines where durability requirements exceed those of any engine developed to date. Typical requirements may include very long service life--10 years or more; very high cycle life--perhaps half a million cycles in the operational lifetime; multiple reuse capability with or without refurbishment--such as in Space Shuttle, reusable satellites, or replaceable Space Station propulsion modules; capability of undergoing multiple launch and re-entry cycles and surviving the range of environments associated with this, such as in the Space Shuttle.

Much effort in the past several years has been devoted to the development and demonstration of beryllium rocket engines, and the technology associated with the thermal and structural design is well known. Applications have included missile postboost control systems, Mariner Mars '71, and Viking Orbiter '75. The beryllium engine concept employed on these programs and further development at Rocketdyne on independent research and development (IR&D) programs, have indicated the potential to meet the reusable, long-life requirements of future vehicles.

The unique properties of beryllium were employed first in 1964 to demonstrate the feasibility of a new rocket engine design concept. This concept used the low density, high thermal conductivity, strength at elevated temperature, and chemical inertness of beryllium to implement an entirely new approach to rocket engine cooling. This process is known as INTEREGEN (INTErnal REGENerative) cooling, and is covered by U.S. Patent 3,439,503. As shown in Fig. 1, INTEREGEN cooling causes

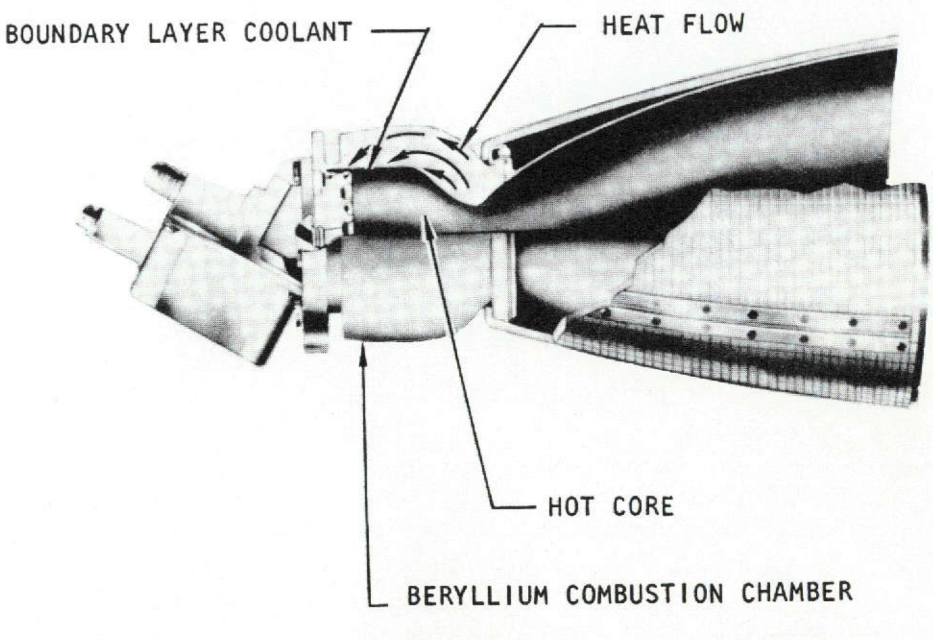


Figure 1. INTEREGEN Cooling Concept

the heat input to the throat and combustion zone areas to flow through the highly conductive beryllium combustion chamber walls to an internally (fuel) cooled boundary layer region near the injector. Both the sensible and latent heat of vaporization of the fuel are used to INTEREGEN cool the thrust chamber. Thermal equilibrium is possible over a wide range of operating conditions. A unique feature of INTEREGEN cooling is its three-dimensional heat-dissipation characteristic provided by the beryllium mass and its high resistance to erosive or burnthrough failures due to localized hot spots (streaking injector with plugged primary on film coolant orifices).

The objective of this program was to evaluate the potential applicability of beryllium rocket engines to reaction control systems of vehicles requiring long service life, and for multiple reuse cycles including repetitive launch/re-entry cycles. The engine design had features not previously used (i.e., brazed injector/chamber joint, insulated columbium nozzle extension) to achieve maximum durability and reuse capability with minimum servicing and maintenance. An objective of this program was to evaluate these new design features. The four-phase program identified beryllium engine capabilities through a program of analysis, design, fabrication, and test.

Phase I was directed toward establishing the engine assembly configuration and operating characteristics through design and analysis. Fabrication of a flight engine assembly and a vibration simulator was accomplished under Phase II. During Phase III the vibration simulator was exposed to the Space Shuttle random vibration environment, and the flight engine was exposed to an endurance test sequence consisting of alternating sequences of simulated mission duty cycles with environmental test sequences. Tests also were performed to demonstrate engine operation under off-limits conditions. Test data analysis was performed under Phase IV, and the flight design updated based on test results.

SUMMARY

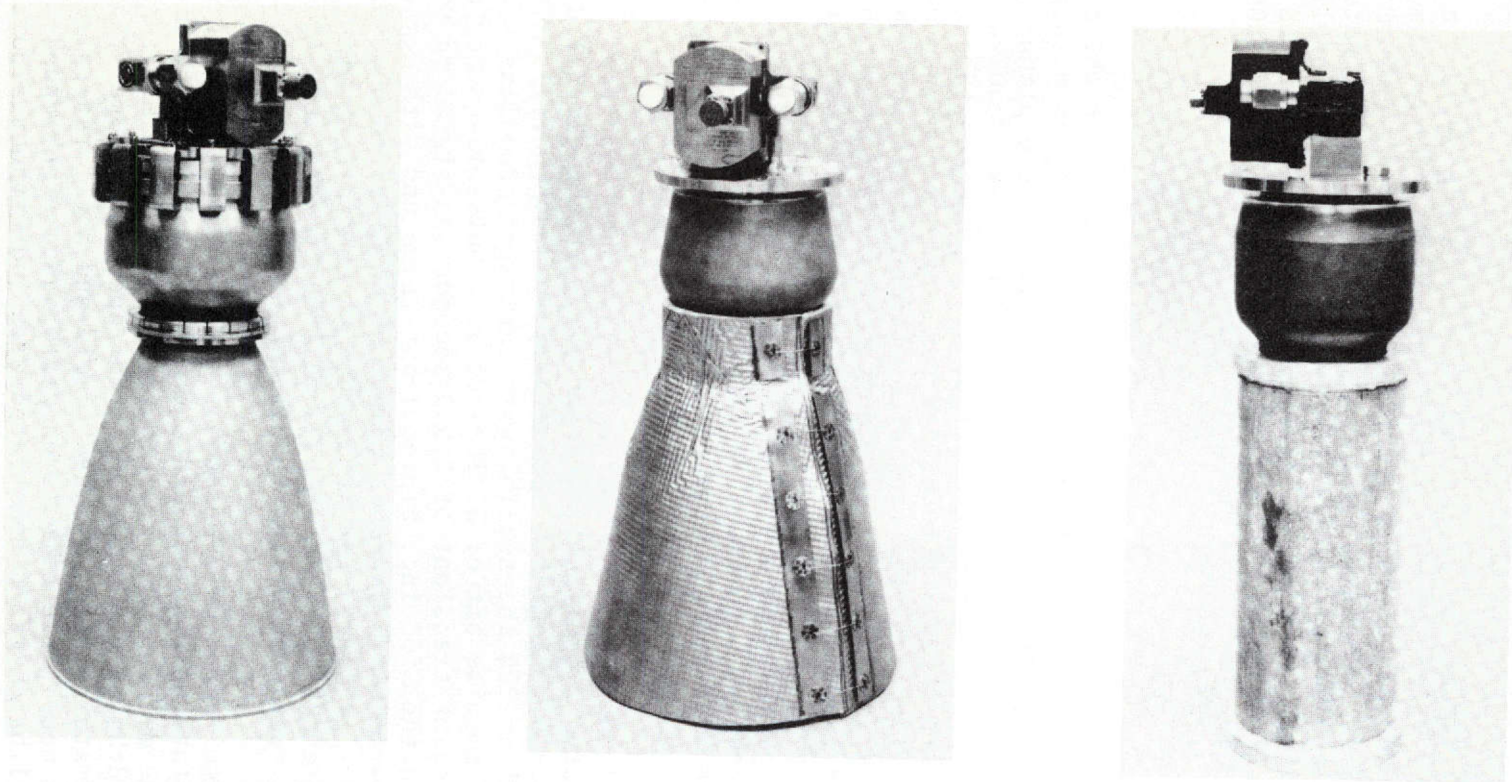
A 600-pound thrust (vacuum) Durability Engine, an Off-Limits Engine, and a Vibration Simulator (Fig. 2) were rigorously evaluated by hot-fire and environmental testing. The test program was conducted to establish the baseline performance and thermal characteristics of the beryllium engine, thoroughly investigate hot-fire and environmental cycle endurance capability, verify ability of beryllium engine to withstand off-limit operational conditions, and expose the brazed configuration by way of a simulated engine to vibration durations equal to 100 simulated Space Shuttle missions.

DURABILITY ENGINE

The purpose of the Durability Engine test program was to demonstrate the multiple reuse capability of a beryllium engine without cleaning, service, or maintenance. Five sequential exposures to hot-fire and environmental tests were planned, but because of valve problems, modifications to the test sequence was required. The test program consisted of exposing a flight configuration 600-pound thrust engine to five hot-fire series at simulated altitude, and six environmental test series. The first three environmental test series consisted of sequential exposure to simulated rain, humidity, salt atmosphere, sand/dust, and vibration with hot-fire between each set. The fourth, fifth and sixth environmental test series consisted of sequential exposure to simulated rain, sand/dust, and vibration with the valve pressurized with 300 psig GN_2 during vibration. GN_2 purges were carried out between the fourth, fifth and sixth environmental test series to simulate engine firing effects. A hot-fire test followed the completion of the sixth environmental test series.

The engine demonstrated 290 and 294.4 $lb_f\text{-sec}/lb_m$ steady-state specific impulse with saturated and unsaturated propellants, respectively, at the nominal design point with a nonoptimum nozzle contour (1.4 second performance penalty). The pulse specific impulse goal of 220 $lb_f\text{-sec}/lb_m$ with saturated propellants was demonstrated for a minimum impulse bit of 30 lb_f-sec at a pulse frequency of 5 cycles/second. An engine start transient of 0.040 seconds (on-signal to 90 percent) was demonstrated with the MOOG Inc. bipropellant valve and with a maximum pressure overshoot of 20 percent. A shutdown transient of 0.020 second (off-signal to 10 percent chamber pressure) was attained. At nominal operating conditions with a 30 psid valve and allowing a 10 psid calibration orifice, the inlet pressure is 290 psia which meets the design requirement.

The maximum single burn requirement of 600 seconds for the Durability Engine was demonstrated with steady-state performance and thermal equilibrium conditions achieved. During the pulse mission duty cycle over which 1/3 to 5 Hz frequency was demonstrated with pulse widths of 0.050 to 1.0 second operation, lower than steady-state mean operating temperatures were obtained. Cold and hot first pulse operation was demonstrated with negligible effects on performance experienced. Durability Engine thermal equilibrium was demonstrated with and without a nozzle extension insulation blanket, with and without helium saturated propellant, including tests in which four film coolant holes were plugged.



OFF-LIMITS ENGINE

- 694 STARTS - 6033 SEC
- 66-235 PC
- 1.3 - 3.0 MR
- PLUGGED ORIFICES

DURABILITY ENGINE

- 500 STARTS - 1451 SEC
- 6 ENVIRONMENTAL CYCLES

VIBRATION SIMULATOR

- 100 MISSION 3 AXIS RANDOM VIBRATION

Figure 2. SS/RCE Technology Program Engines

For the baseline performance test, thermal equilibrium was reached in 200 seconds of on time. A maximum temperature of 500 F was recorded at the throat OD. The measured peak nozzle temperature was 2000 F. The recorded beryllium temperatures were relatively unchanged by insulation of the nozzle. However, the peak nozzle temperature was increased by approximately 150 F when thermally insulated. Nozzle insulation OD peak temperature exceeded the 800 F requirement by 75 F, but this can be corrected easily by emissivity control of the outer shell or minor thickening of the insulation. The maximum valve temperature was 200 F after 30 minutes of thermal soak which presents no problem to valve integrity or restart performance

Up to four film coolant holes were plugged in the injector during exposure to environmental conditioning. The plugging was detectable during subsequent hot-fire tests in measured beryllium temperatures since the average value was 600 F and a peak of 835 F was recorded downstream of the plugged region. The plugged coolant orifices caused only slight oxidation of the throat ID. The beryllium combustor maximum head end temperature was increased by approximately 20 F and measured nozzle temperatures were unchanged.

Posttest thermal analyses have been made of the engine and indicate that the beryllium chamber can be reduced in weight by approximately one-half pound while maintaining INTEREGEN operation. Additional weight savings can be gained by going from the present 6:1 contraction ratio to 4:1. The injector alone could be reduced by 3.8 lb_m.

The six environmental cycles of testing had no adverse effect on the engine other than slight superficial staining and pitting of the beryllium chamber. However, detrimental effects were sustained by the MOOG Inc. bipropellant torquemotor valve because of sand/dust and vibration. Severe damage was sustained by the valve seats during environmental testing from migration of sand/dust particles between the poppet and seat during vibration sequence even under specification lockup inlet pressures. The valve, which was designed to meet an inlet pressure of 300 psia, also exhibited problems opening at higher inlet pressures for certain tests.

The engine successfully completed the sinusoidal vibration testing with no evidence of detrimental effects. During random vibration testing, strain gage data indicated that low-frequency resonant modes were present in the 150 to 250 Hz frequency range. Strain values recorded in the braze transition joint between the injector and chamber were on the order of one-half that allowed in the design. Therefore, the design is capable of withstanding inertial loads greater than twice those experienced in test. Analyses have shown that the Durability Engine design exceed Space Shuttle life requirements. The success of the test program has corroborated these predictions on life.

The combustion stability characteristics of the Durability Engine injector were evaluated under a company-sponsored program. The average overpressure ranged from 574 to 882 psia. The rise rates were all greater than 1 psi/msec and average damp times were 12 msec or less. All data indicate that the tests were valid indication of the dynamic stability characteristics of the engine.

OFF-LIMITS ENGINE

The purpose of the Off-Limits Engine test program was to demonstrate the ability of a beryllium INTEREGEN engine to operate over a wide range of propellant inlet pressures and with multiple orifice plugging. The Off-Limits Engine demonstrated very broad off-limits operation capability (1.43 through 2.88 o/f mixture ratio and 66 through 230 psia chamber pressure) without sustaining damage. However, during the worst case (simulated dual oxidizer regulator failure - 2.88 o/f mixture ratio with 238 psia chamber pressure) operation, high temperatures in the Haynes 25 nozzle extension caused a failure of the material. This test was repeated successfully with this same engine with a columbium nozzle extension on a company-sponsored program. The Off-Limits Engine was tested to steady-state conditions with one plugged primary fuel hole and with one and three adjacent plugged coolant holes. The engine throat OD temperatures reached predictable values which demonstrated the feasibility of reliable engine shutdown devices to allow for subsequent engine operation. The plugged coolant orifice caused only slight oxidation of the throat ID downstream of the plugging.

VIBRATION SIMULATOR

The purpose of the Vibration Simulator test program was to demonstrate the structural integrity of the chamber/injector joint by exposing a flight configuration joint to random vibration equivalent to 100 Space Shuttle missions. The measured peak strain amplitude was less than one-half the design value. Therefore, the injector/chamber braze joint can withstand inertial loads greater than twice those experienced in test. Posttest proof pressure at 500 psig and leak tests at 200 psig verified the structural integrity of the simulator and demonstrated the high reliability of the beryllium braze joint.

SUMMARY OF RESULTS

Posttest examination of all thrust chamber assembly hardware indicated it to be in excellent condition. High cycle life was demonstrated by the attainment of low beryllium chamber operating temperatures and thermal gradients. The low operating temperatures at nominal conditions provide large thermal margin which allows for operation over a wide range of inlet conditions.

The results from this program indicate the ability of the beryllium INTEREGEN engine concept to meet the operational requirements of the Space Shuttle reaction control system.

ENGINE REQUIREMENTS

The beryllium rocket engine for this program is a pressure-fed, pulse-modulated, hypergolic, bipropellant engine designed to meet the requirements and performance goals of Table 1. The engine must be capable of long life and multiple reuse when sequentially exposed to launch pad and launch environment, vacuum and high-altitude operation in any attitude, and landing area environment with minimum maintenance for 100 missions. Within the constraints of the per mission requirements of 1000 seconds total firing time, 600 seconds maximum single burn, 30 lb-sec minimum impulse bit, 5 pulses/second maximum frequency, and 2000 pulses/mission the engine should be capable of performing any combination of burns without excessive soakback to the injector/valve assembly, which could cause valve damage or propellant vaporization. The engine must be capable of safe operation over a wide range of chamber pressures and mixture ratios and with injection orifice partial or total blockage causing oxidizer spray on the wall or localized film-coolant interruption.

The nominal design point is 600 pounds thrust, 200-psi chamber pressure, NTO/MMH propellants at a 1.63 o/f mixture ratio, and 40:1 nozzle extension. However, the engine concept should be scaleable over a 100- to 1100-pound-thrust range, and the nozzle should be capable of scarfing to fit a vehicle mold line when installed in a buried mode. The engine was designed to provide maximum performance consistent with life and thermal margin requirements, with the performance goals listed in Table 1.

TABLE 1. DESIGN REQUIREMENTS AND PERFORMANCE GOALS

Design Requirements	
Thrust, Vacuum, pounds	600
Steady-State Chamber Pressure (P_c), psia	200
Engine Steady-State Mixture Ratio (o/f)	1.63
Exhaust Nozzle Area Ratio (ϵ)	40:1
Propellants	
Oxidizer	N_2O_4 (MIL-P-26539C MON-1)
Fuel	MMH (MIL-P-27404)
Pressurant	Helium (MIL-P-27407)
Propellant Feed Conditions	
Static Pressure, psia	300 ±6
Dynamic Pressure, psia	290 ±10
Temperature, F	75 ±35
Valve Voltage, vdc	28 ±4
Installation	
Within a Vehicle Mold Line; Max. Outer Surface Temperature, Engine Assembly (environment 300 F), F	800
Engine Weight and Envelope	Minimized
Minimum Impulse Bit (nominal conditions), lbf-sec	30 ±10
Maximum Pulse Frequency, cps	5
Maximum Single Firing, seconds	600
Maximum Firing Time per Mission, seconds	1000
Maximum Number Pulses per Mission (including 75 full thermal cycles)	2000
Engine Life	
Missions	100
Years	10
Burn, seconds	100,000
Pulses (including 7500 full thermal cycles)	200,000
Stability	
Chamber Pressure (nominal steady state), %	±5
Chamber Pressure (periodic or cyclic 2000 Hz),%	±8
Performance Goals	
Specific Impulse (nominal conditions $\geq$ 1 sec), lbf-sec/lbm	295
Pulsing Specific Impulse (MIB nominal conditions, lbf-sec-lbm	220
Specific Impulse Shift (nominal range conditions)	Minimized
Mixture Ratio Shift (nominal range conditions)	Minimized
Engine Start Transient (signal ON to 90% P_c), seconds	< 0.050
Engine Shutdown Transient (signal OFF to 10% P_c), seconds	< 0.050
Off-Limits Operating Capability	
Engine design capable of broad off-limits operation without sustaining damage. This includes feed pressure ranges (both common to each propellant and mismatched), feed temperature ranges, valve voltage ranges, valve opening and closing mismatch, operation with gas bubbles, blockage of injector orifices.	

PHASE I--ENGINE ANALYSIS

The principal components of the beryllium INTEREGEN engine are: (1) a single-stage, bipropellant valve; (2) a high-performance, multielement, unlike-doublet injector; (3) an INTEREGEN-cooled beryllium thrust chamber; (4) a thin-wall nozzle extension; and (5) an insulation blanket. Figure 3 shows assembly drawings for the flightweight brazed configuration (Durability Engine), the bolted configuration (Off-Limits Engine), and the Vibration Simulator used to demonstrate braze joint structural integrity.

DURABILITY ENGINE DESIGN

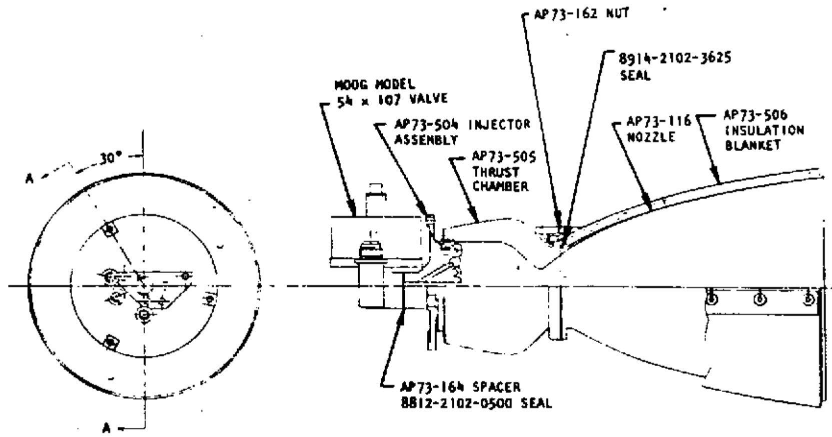
All components and assembly hardware on the Durability Engine are flightweight with the exception of the back side of the injector, which was designed to mate with an existing Moog valve and hot-fire test facility.

The thrust chamber for the Durability Engine is composed of a combustion chamber fabricated of aerospace grade, hot-pressed, sintered beryllium; a nozzle extension fabricated of WC103 columbium diffusion coated with the Vac Hyd silicide coating VH-101; and an insulation blanket. The chamber is cylindrical, has a 16.0-inch characteristic length, a 6:1 contraction ratio, and is contoured to optimize the INTEREGEN-coolant film effectiveness. Design improvements were made relative to previously tested INTEREGEN thrusters (i.e., Minuteman III PBPS, Mars Mariner '71, Viking Orbiter '75, RM1000 which resulted in a 20 to 30 percent reduction in heat transfer).

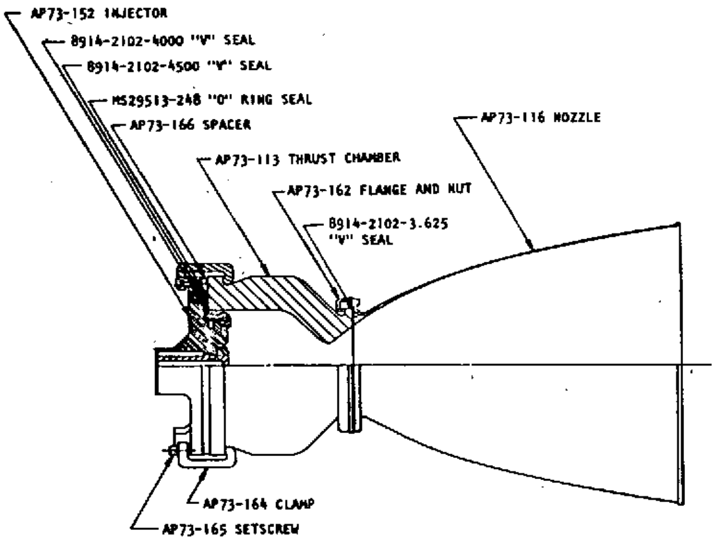
A coated columbium nozzle was selected in place of the cobalt-base-alloy, Haynes-25 configuration used on the Mars Mariner '71 and Viking Orbiter '75 engines to provide thermal margin at extreme off-limits operating conditions. The nozzle incorporated an 80-percent bell and extended from the 3:1 beryllium attach point to 40:1. A special nozzle contour, originated to reduce nominal nozzle operating temperature of a Haynes-25 nozzle from 2000 to 1900 F, was used. The nozzles are attached to the chamber at an expansion ratio of 3:1 through a flexible Rene' 41 flange and threaded nut arrangement identical in configuration to that employed in the Mars Mariner '71 and Viking Orbiter '75 engines. The nozzle is insulated by Dynaflex, a flexible insulation material manufactured by Johns-Manville, which is encased in a thin titanium jacket. This material was selected over Min-K used on the Minuteman III PBPS beryllium engine due to its higher operating temperature capability.

The injector selected for the beryllium engine is a multielement, unlike-doublet configuration, fabricated from 321 stainless-steel alloy material. This injector was designed, fabricated, and characterized under a company-sponsored program. The injector, which contains 56 elements impinging along three concentric rings, is patterned after a large family of unlike-doublet injectors designed for use with earth-storable propellants in INTEREGEN-cooled beryllium thrust chambers.

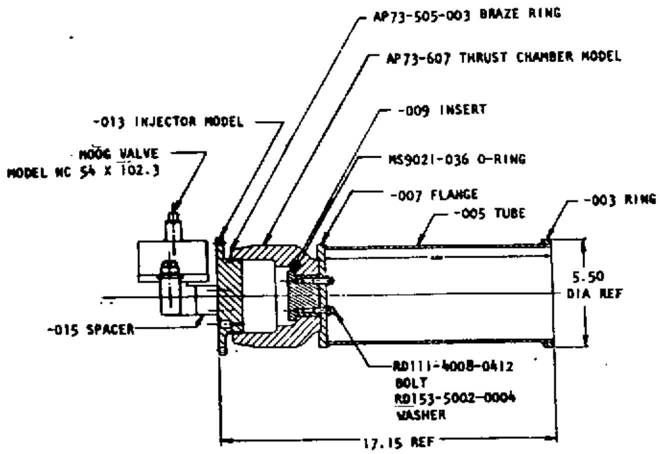
An injection orifice pressure drop of 40 psid was selected to: (1) provide a reasonable performance level (high velocity promotes propellant atomization), (2) provide stability margin during low-pressure operation with helium-saturated propellant should blowdown operation be required, and (3) meet the inlet pressure



Durability Engine Assembly



Off-Limits Engine Assembly



Vibration Simulator Assembly

Figure 3. Engine Test Configurations

requirement of 290 psia when accounting for pressure losses through the injector manifold ($\sim$10 psid), valve ($\sim$30 psid), and engine calibration orifice ($\sim$10 psid).

The injector/chamber interface incorporates a brazed joint configuration specifically developed for the Space Shuttle RCS application under a company-sponsored program. A Haynes-25 ring is brazed directly to the beryllium and the ring is then electron-beam (EB) welded to the CRES injector. A primary objective of the contract is to demonstrate the compatibility and structural integrity of this joint when exposed to successive cycles of hot-fire and environmental conditions typical of the Space Shuttle.

A single-stage, direct-operated bipropellant valve was selected for the beryllium rocket engine. The single-stage design was considered as the most reliable concept with the minimum scheduled maintenance requirements based upon existing flight-proven technology. The Moog, Inc., torquemotor operated, staggered poppet design Model 54X107, developed by Moog for NASA contract NAS9-12976, was selected A design goal of 30-psid pressure drop was specified with the projected valve response time 30 msec opening and 15 msec closing. The valve weighs 4.5 pounds. It is bolted to the injector with thin titanium spacers to insulate the valve from the engine. The insulator contains grooves for V seals between the injector and valve.

OFF-LIMITS ENGINE DESIGN

The engine assembly employed for off-limits tests was made available to the contract from a company-sponsored program. Differences between the Off-Limits and Durability Engines are:

1. Facility valves were used in place of the Moog valve, the latter being unable to open at the elevated inlet pressures required for off-limits testing.
2. A two-ring, 36-element injector was used in place of the three-ring, 54-element configuration.
3. A bolted injector/chamber interface similar to that used on Minuteman III and Mars Mariner '71 engines was used in place of the brazed configuration (beryllium geometry at injector interface modified for bolted configuration).
4. An uninsulated Haynes-25 nozzle was used in place of the insulated coated columbium configuration (nozzle geometry identical for both nozzles).

The injector has fewer elements and a lower manifold volume than the three-ring configuration used in the Durability Engine. The fewer elements result in larger orifices (0.025-inch minimum diameter compared to 0.020-inch on the three-ring design). This injector has lower steady-state performance due to its coarser pattern but higher pulse performance for short pulse widths due to reduced manifold volume.

VIBRATION SIMULATOR DESIGN

The purpose of the vibration simulator is to verify the structural integrity of the brazed injector/chamber joint when subjected to 100 missions of launch vibration (X, Y, Z axes random vibrations). To meet this objective, the simulator was designed to have the same mass and moments of inertia as the flight configuration Durability Engine. Since the primary structural feature being demonstrated is the thrust chamber/injector braze joint, the simulator design in this area is identical to the flight configuration. To minimize cost, the beryllium chamber contouring is minimized and a dummy aluminum nozzle extension is used to simulate the proper mass and inertia. The injector body manifolding and orifices are not included, but again, the proper mass and inertia are simulated. An existing Moog valve whose mass properties are identical to the valve selected for the Durability Engine is bolted to the injector.

DESIGN ANALYSIS

Design analyses have been performed for the Durability Engine whose operating characteristics are representative of a flight configuration. These included evaluation of performance, thermal, structural/life, hydraulic, and stability characteristics; identification of maintainability, reliability, and safety in the Space Shuttle RCS application; and assessment of scaleability of the beryllium engine concept over a thrust range of 100 to 1100 pounds.

Performance

The injector selected for the Durability Engine was previously tested using non-flightweight hardware on company-sponsored programs. Therefore, the performance predictions presented here are primarily based on empirical results.

Steady-State Performance. The Durability Engine predicted steady-state performance is shown in Fig. 4. The data are for nominal NTO/MMH propellant temperature (75 F) and nozzle expansion ratio of 40:1. The 290-second specific impulse at a 1.63 o/f mixture ratio is below the design goal of 295 seconds; however, it can be achieved with minimum development effort. Predictions of 292 and 293.4 seconds at 1.63 o/f mixture ratio are made for unsaturated propellants and optimum nozzle, respectively. The effect of propellant inlet pressure on engine nominal mixture ratio and thrust was established for temperatures 75 ±35 F and pressures 290 ±20 psia. Mixture ratio excursion from 1.46 to 1.83 can occur for the assumed maximum ±10 psia inlet pressure variations. Mixture ratio excursion from 1.59 to 1.67 can occur for variation in inlet temperature of ±35 F.

Pulse Performance. The engine is to be capable of delivering 220 lb_f-sec/lb_m pulse vacuum specific impulse at a minimum impulse bit of 30 lb_f-sec. Constraints on the design were a 50 msec start, 50 msec shutdown, minimum chamber pressure overshoot, and simplicity of manufacture.

The final engine design incorporated a total volume (fuel and oxidizer) downstream of the valve seat to the injector face of 1.63 $in.^3$. This volume is minimized to give maximum pulse performance while allowing a design assuring low propellant

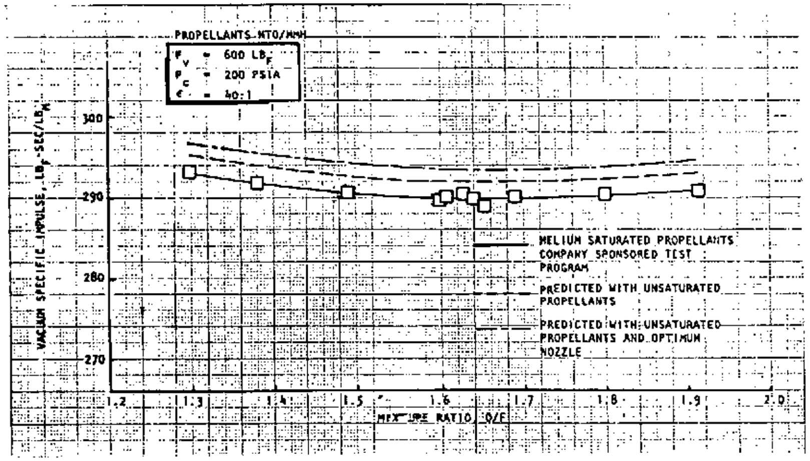


Figure 4. Durability Engine Steady-State Performance

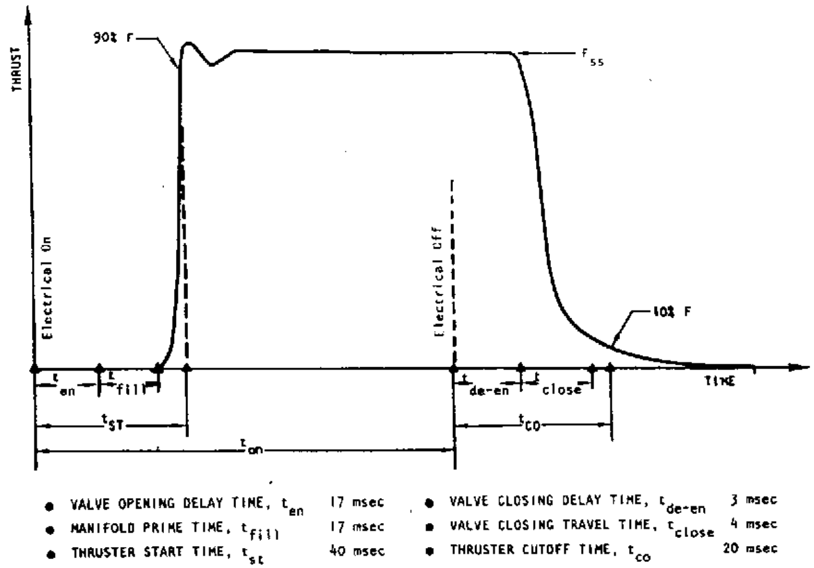


Figure 5. Durability Engine Response Characteristic

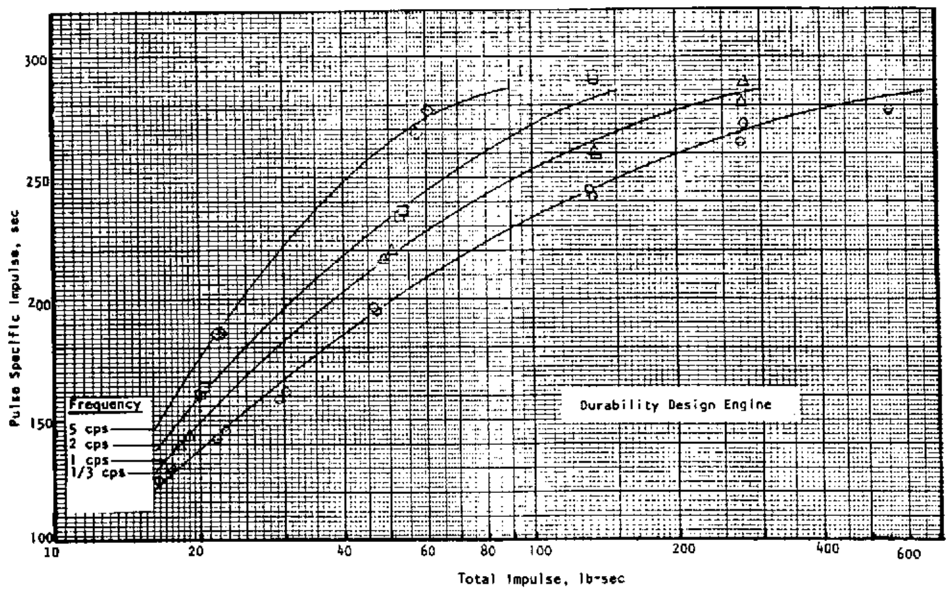


Figure 6. Pulse Specific Impulse vs Total Impulse

velocities and good injector mass flow distribution for uniform heat flux on the chamber walls and for maximum steady-state mixing and vaporization efficiencies. The engine dribble volume is composed of 0.84 in.^{3} fuel volume and 0.79 in.^{3} oxidizer volume, which theoretically led to a maximum 50-percent overshoot using worst-case assumptions. In fact, the overshoots observed were 20 percent or less. No other manifold or residual propellant explosions or pressure spikes were observed during the Durability Engine testing.

An idealized engine pulse is shown in Fig. 5. The observed delay between on signal and first valve movement was 17 msec. The time require to prime the fuel manifold, the first to fill, was 17 msec also. From first fuel to the combustor, then first oxidizer, ignition delay and buildup to 90-percent thrust was 6 msec. This 40-msec start time is faster than the engine specification of 50 msec. Valve closures requires very little time, 3 msec for de-energize, and then 4 msec to move to the closed position. The time required to reach 10-percent thrust from off signal varied from 15 to 20 msec during the testing. Zero thrust was reached approximately 700 msec after off signal. Shutdown impulse averaged about 9 lb_f-sec. As pulse frequency increased, maniforld prime time decreased asymptotically to about 7 msec due to entrapped propellant. Hardware temperature had little effect on the pulse characterization times.

The hot-fire pulse performance study consisted of more than 300 pulses using helium-saturated NTO/MMH with valve electrical on times from 50 to 100 msec. Pulse frequencies ranged from 0.25 to 5 pulses per second. No significant difference was observed between pulses run with ambient hardware and with hot hardware immediately following an extended steady-state run. Hot-fire data are presented in Fig. 6, summarizing pulse total impulse, pulse vacuum specific impulse, and pulse frequency. The data show that this design meets the design pulse requirements at the 5 cps frequency. The run-to-run repeatability observed in hot-fire testing of this engine assembly was 3 lb_f-sec at the 95-percent confidence interval.

Thermal Analysis

Nominal Operation. The Durability Engine has been designed to meet the thermal requirements of the SS/RCS. A unique thermal analysis engine model has been developed at Rocketdyne to perform the required analyses to design optimum INTEREGEN thruster configurations.

The combustor design has been optimized to achieve the thermal margin for INTEREGEN cooling and meet the design requirements and performance goals of the RCS beryllium engine. The thermal analyses have been based on using 40 percent of the fuel (15.2-percent total propellant flow) to provide boundary layer coolant and insulation of the nozzle with Dynaflex material to reduce the external surface of the assembly to 800 F. The results of the thermal analysis of the optimized design are presented in Fig. 7, which illustrates the internal and external steady-state temperature distribution for the Durability Engine as a function of axial length.

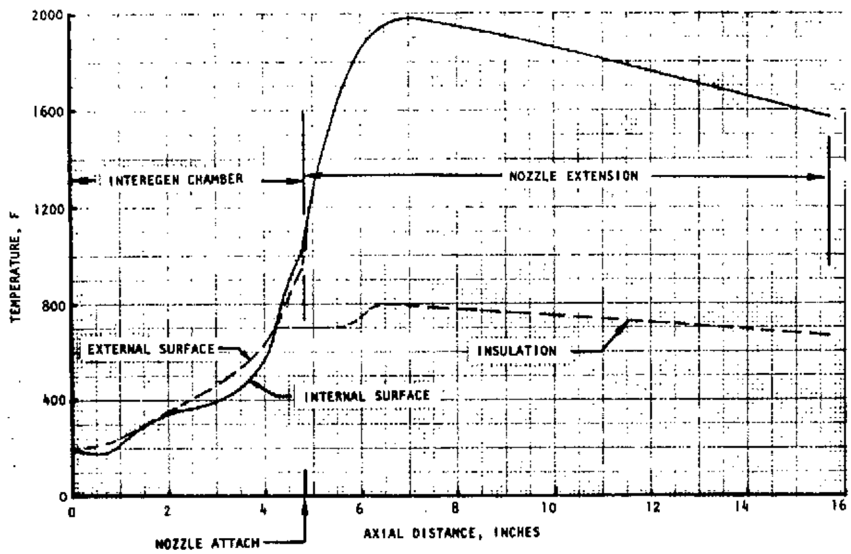


Figure 7. Durability Engine Predicted Temperature Profile Steady-State Operating Conditions

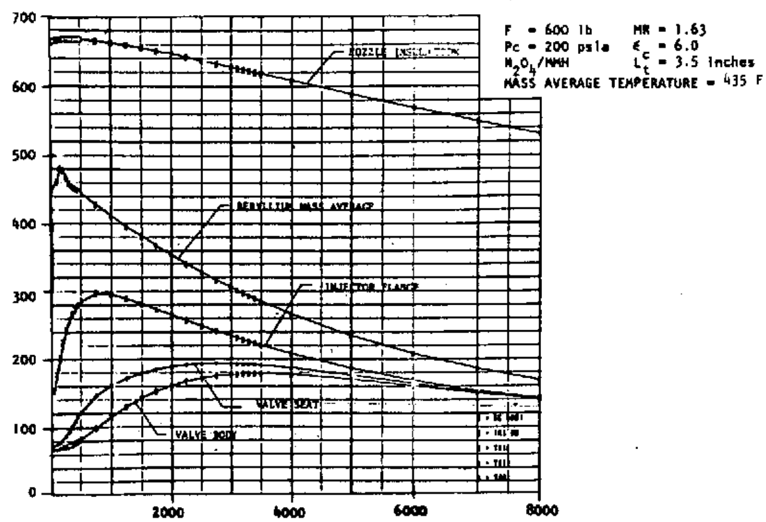


Figure 8. Soakback Analysis Predicted Temperature Response

The time to steady-state temperatures is approximately 200 seconds. This long temperature transient minimizes the thermal cycle requirement of the engine. The mass average beryllium temperature (Fig. 8) is 435 F, which eliminates any restart problem and minimizes thermal soakback to the injector and valve at thruster shutdown. The effect of saturated propellant on INTEREGEN cooling has been evaluated on the MM III, MM '71, and IR&D programs. Both He- and GH_2-saturated propellants have been tested without any measurable affect on thermal characteristics.

Off-Limits Operation. Off-limits operation of the baseline advanced beryllium engine was performed for steady-state operating effects. The design was analyzed for inlet propellant temperature of 75 ±35 F and inlet propellant pressure of 290 ±20 psia, which produced a resultant range in mixture ratio of from 1.32 to 2.05 o/f. The results of the analysis indicate a maximum beryllium temperature of 1465 F at the combined high mixture ratio and high inlet propellant temperature condition.

Thermal Soakback. Thermal soakback from the thrust chamber to the injector-valve assembly by conduction, convection, and radiation was evaluated to determine maximum operating temperature. The results of the analyses (Fig. 8) show that the maximum external temperature requirement of 800 F and the 200 F maximum allowable valve seat temperature will be satisfied.

Streak Heating. Thermal analyses were conducted of the Durability Engine for a unit length section in the throat plane to determine the effects of no film cooling over a defined streak width. Various multiples of the gas side film coefficient and streak width were considered.

Beryllium throat oxidation occurs at approximately 1800 F and surface erosion at 2300 F. The results of the analysis (Fig. 9) indicate that with nominal gas side heating oxidation and surface erosion are predicted to occur with streak widths of 1.4 and 1.9 inch, respectively. With an assumed streak width of 0.50 inch, multiples of 3 and 5 on gas side heat transfer coefficient are required for surface oxidation and erosion, respectively.

Structural and Life Analysis

Pressure, thermal, and thrust loading, as well as anticipated flight inertial loading, were used in evaluating the structural and life requirements of the Durability Engine. Basic structural criteria consisted of maintaining a minimum yield safety factor of 1.2 and a minimum ultimate safety factor of 2.0 based on minimum guaranteed material properties and maximum primary stress with thermal, pressure, thrust, and inertia loads applied. A safety factor of 10 was used for all fatigue analyses.

The Durability Engine was designed to the shuttle vibration requirements, which resulted in the following inertial loading for the engine structural analysis:

Axial Inertia Loading	360 G units
Lateral Inertia Loading for the Nozzle	143 G units
Lateral Inertia Loading for the Combustor/Nozzle Assembly	100 G units

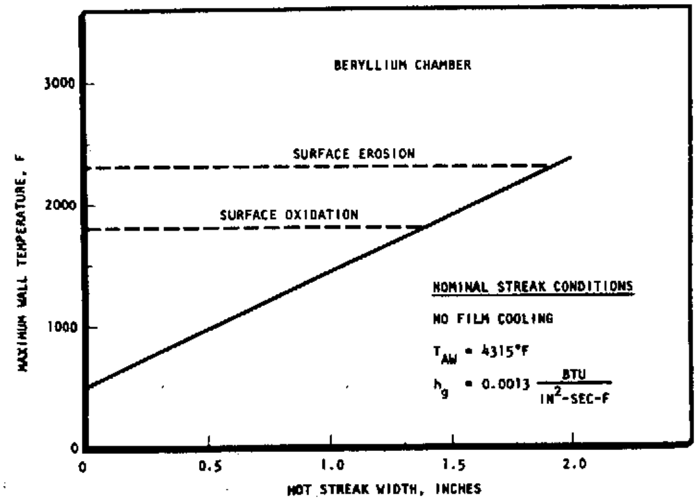


Figure 9. Effect of Hot-Streak Width on Throat Temperature

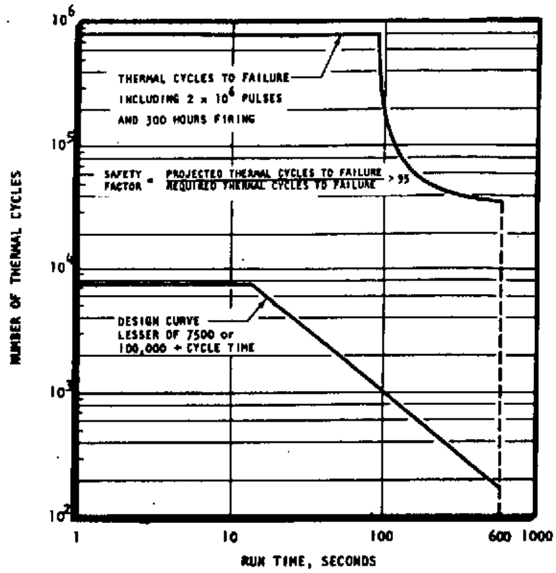


Figure 10. Durability Engine Cycle Life

TABLE 2. DURABILITY ENGINE HYDRAULIC CHARACTERISTICS SUMMARY

Moog Valve (54-109)	
Manifold Volume, in.^{3}	
Oxidizer	0.134
Fuel	0.134
Injector (Fuel Configuration)	
Manifold Volume, in.^{3}	
Oxidizer	0.6536
Fuel	0.7127
Maximum Velocity, ft/sec	
Manifold Oxidizer	22
Manifold Fuel	22
Injection Orifice Oxidizer	66
Injection Orifice Fuel	83
Pressure Drop, psid	
Manifold	10
Orifice	40

Life Evaluation. A life evaluation of the beryllium combustor was conducted and the expected life found to be well within design goals. A finite element model was prepared for the purpose of calculating thermal strain. The fundamental theory used in the life prediction analyses is that failure depends on the accumulation of creep damage and fatigue damage. A study of thermal gradients developed during pulsing indicated that the strain excursions for individual pulses will be below the elastic limit of beryllium and, therefore, a fatigue capability on the order of the endurance limit is expected (10^7 cycles) for pulse mode operation. A train of pulses is equivalent to one full thermal cycle whose equivalent steady firing time is approximately equal to the accumulated pulse on time. The cycles to failure plotted in Fig. 10 indicate a very high margin of safety.

Hydraulic Analysis

A complete hydraulic analysis of the valve and injector (also effects of feed system) was conducted. A summary of the engine hydraulic characteristic is shown in Table 2.

Combustion Stability Analysis

The two common instability modes (feed system coupling and acoustic) have been considered in the engine design. The primary consideration for feed system coupling are the available injector pressure drop (relative to chamber pressure), engine physical size, and propellant combination. A $\Delta P/P_c$ ratio of 25 percent was selected for this engine, which compares favorably with the $\Delta P/P_c$ ratios present in previously stable engine configurations employing the same propellants with saturated helium. Thus, feed system coupling is not expected to occur with the Durability Engine design.

In acoustic stability, the primary considerations are injection scheme, engine size, propellant type, and the mechanism involved in interaction of the burning process with wave notions within the gas of the combustion zone (as opposed to interaction of the burning process with natural wave motions of the feed system, i.e., feed system coupling).

The Durability Engine design employs a straight acoustic slot (0.080-inch wide by 0.750-inch deep), which results in an absorber open area of 7.0 percent. This value places this engine design close to both the stable LM-A engine and Minuteman III engine absorber designs. The Durability Engine design is expected to have completely satisfactory stability characteristics because of the incorporation of acoustic cavities along the injector periphery.

Combustion Stability Test. The combustion stability characteristics of the Durability Engine injector were evaluated under a company-sponsored program using a Moog bipropellant valve. Three bomb tests were conducted using six charges (two charges set off during each test). The average damp times were 12 msec or less and were governed primarily by lower frequency disturbances that are considered of little consequence. The high-frequency disturbances all damped in significantly shorter times. The frequencies in the vicinity of 8000 to 12,000 Hz correspond to the first- and second-tangential modes of the chamber as expected. The data indicate that the engine was adequately designed to damp these modes.

Scaleability

The scaleability of beryllium engines is illustrated by the broad range of engines built to date. Sixteen beryllium engine models, which cover a chamber pressure range of 50 to 400 psia and thrust level of 1 to 1600 lb_f, have been developed with >420,000 starts and >500,000 seconds burn time accumulated. Beryllium engines have been qualified and flown in the Minuteman III PBPS (>700 units produced to date), Mars Mariner '71 vehicles (10 months operation in space) and the Viking Orbiter '75 (~20,000 seconds accumulated on single DDT&E units).

The maturity of the beryllium engine technology is demonstrated by the following:

- Single engines have demonstrated these hot-fire capabilities with no apparent physical degradation:

Single burn duration	10,000 seconds
Total burn duration	25,764 seconds
Start and pulses	58,000

- Fabrication

  961 engines produced (Durability Engine size)
  831 engines delivered

- Flight

  75 flights with 100 percent reliability
  10 months of operation in space

The beryllium INTEREGEN engine is currently in its fourth generation of development. Improvements in cooling efficiency and assembly have been introduced and demonstrated for the Durability Engine to provide an engine that meets the high-cycle-life, multiple reuse requirements of the Space Shuttle.

Reliability, Safety, and Maintainability Analyses

The beryllium engine flight configuration was evaluated relative to reliability, safety, and maintainability criteria for the SS/RCS application. In performing this assessment, it was assumed that the torquemotor bipropellant valve would be designed specifically for the point design configuration.

The SS/RCS beryllium engine incorporates design concepts proved to be reliable, safe, and maintainable in engines designed for multiple use in single missions, and ground tested in multiple missions. This design meets both material aging and wearout goals of the Space Shuttle. The beryllium engine is capable of operating safely and reliably in two firing modes (the INTEREGEN-cooled and the heat sink mode). Redundancy in cooling is inherent in the design because of the high conductivity and thermal capacity of beryllium. Flight instrumentation and post-flight visual inspection will provide necessary fault detection/isolation information. Key design features which lead to high reliability and fail-safe operation are:

Margin of strength	Flight-proven design concepts
Off-limits margin	Positive isolation of propellants
Redundancy in engine cooling	Demonstrated material compatibility
Design simplicity	Easy decontamination
All-metal construction	Flight instrumentation for fault detection/isolation

Reliability. Key design characteristics included in the preliminary design that contributed to achievement of high inherent reliability are listed in Table 3. A Failure Mode, Effect, and Criticality Analysis (FMECA) of the engine was made to assess the reliability of the baseline design (Table 4).

Safety. The RCS engine is safe to operate and maintain because of the (1) fail-safe design concepts; (2) strength margins at operating pressures and temperatures; (3) life margin; (4) positive isolation of propellants; and (5) ability to operate at off-design conditions of mixture ratio, propellant temperature, combustion pressure, and boundary layer coolant (BLC) flow. These safety margins have been established through analysis and also from test data on similar engines (i.e., the Mars Mariner '71 engine that ran successfully with restricted BLC flow). The materials are thermally forgiving because of their durability and high thermal conductivity. The engine has a long time margin to failure due to its configuration, durability, high thermal conductivity, thermal capacitance cool operation, and thermal capacitance.

The cooling principle leads to low operating temperatures, which result in high thermal, structural, life, and time to critical failure margins. The design is relatively insensitive to off-design operation and has no duty cycle constraints. The heat capacity of the thrust chamber permits firing durations up to 50 seconds without any coolant flow before a critical burnthrough failure will occur. This highly abnormal possibility can be readily detected before critical failure and engine firing terminates.

A potentially hazardous condition can exist from the inhalation of beryllium metal or its compounds during fabrication. Operations such as machining, filing, grinding, polishing, etching, or other processing that may produce airborne concentration of beryllium materials are controlled at Rocketdyne by accepted industrial safety procedures. More than 800 beryllium thrust chambers have been manufactured at Rocketdyne since 1964 without incident. Industrial processing of beryllium material is wide spread, particularly at Rockwell International divisions. This is due to its attractive properties for electronic, aircraft, and space applications.

Beryllium particles are not released during or after engine operation because of the extremely low operating temperature of the thrust chamber, 1000 F at all conditions, including off-limits; a temperature of 1800 F is the point at which beryllium oxidation occurs. Established safety precautions exist to cover a hazardous condition should a malfunction or accident occur that releases beryllium particles.

TABLE 3. KEY DESIGN CHARACTERISTICS

Reliability Features	Engineering Design Features
	Rocket Engine Assembly
Simplicity	Few parts
Insensitivity to environments	Demonstrated durability
Reuseability and design marging	Demonstrated cycle life
Life and reuseability enhanced	Excellent thermal management producing super-cooled surfaces
Insensitivity to heat	Titanium insulators between valve and injector
Insensitivity to thermal and pressure cycles	Low operating temperatures and material stress levels. High margins of safety
	Bipropellant Valve
Simplicity	Few parts, single-stage, scalable, no vents
Insensitivity to Environments	Demonstrated durability and material compatibility; motor hermetically sealed; thermal isolation
Reuseability	No sliding fits, material compatibility, inlet filter
Life	Demonstrated concepts, compatible materials, welds and metal seals, durable seat, inlet filter
Fail-safe	Valve poppets biased to fail closed; welds and metal seals
Simultaneity	Mechanically linked poppets
Positive propellant isolation	Parent material, redundant seals, captive Teflon seat, inlet filters, compatible materials
Ability to clean	Inlet filters, simple contour, no sliding fits, compatible materials
Insensitivity to heat	Propellant-cooled seat, titanium space insulator, minimum Teflon volume
Valve position, flight monitoring	System instrumentation - chamber pressure, valve command signal
	Injector
Simplicity	Symmetric, uniform pattern and passages, no baffles, scalable, even distribution
Durability	Unlimited life, low face heat flux
Reuseability	Compatible materials, all-welded design
Life	Demonstrated performance, compatible with chamber, compatible materials, state-of-the-art design
Stability	Acoustic cavity demonstrated operation, positive ignition with unlike doublets, thousands of firing on variety of engine shapes, sizes, propellants and performance levels.
Positive propellant isolation	Parent material, machined; all EB welded, 100% inspectable; all EDM drilled passages in quality material bar stock.
	Thrust Chamber
Simplicity	Single piece
Durability	Compatible materials, thermally forgiving, high strength
Reuseability and Life	Compatible materials, thermally forgiving, demonstrated concept on variety of engine shapes, sizes, propellants and performance levels.
Insensitivity to heat	Thermally forgiving, INTEREGEN-cooled, radiation-cooled nozzle
Simplicity	Single piece
Durability	Compatible material, high strength, compatible with environments
Life	Demonstrated performance, compatible materials
Insensitivity to heat	Compatible, high-strength material, single piece, insulated, radiation cooled

TABLE 4. FAILURE MODE, EFFECTS, AND CRITICALITY ANALYSIS

Component/Function	Failure Mode	Criticality	Failure Effect		Preventive/Corrective Measures	Detection/Isolation
			Engine	Vehicle		
Seal, Valve to Injector Confine propellant within the defined flow passages	External leakage	Minor	No effect-Redundant seals	No effect	Redundant gold plated Inconel X omega seals on each flow passage. Bolted assembly. Titanium spacer plate.	Periodic visual inspection
Injector Assembly Injects propellants into thrust chamber in prescribed manner to ensure controlled ignition and satisfactory combustion	Poor combustion Plugging	Minor to Critical	Irregular thrust, instability Throat Erosion	No effect to poor vehicle response No effect	EDM precision drilled orifices; stable operation capability over wide pressure range; INTEREGEN cooling combined with high thermal conductivity of beryllium automatically dissipates local heating, thermal malfunction device can be used to shut down engine prior to erosion or nozzle failure	Condition monitored chamber pressure correlations Visual Inspection
	Instability	Major to Catastrophic	Rapid structural damage	No effect (redundant engines) to potential vehicle fire	Proven acoustic cavities for damping	Not required (failure mode not credible
	Internal leakage	Critical Catastrophic	Potential Explosion, structural damage	Explosion and fire in vehicle pod	Parent material between propellants; machined bar stock, parent material	Not required (failure mode not credible)
	External leakage	Critical	Minor leakage no effect; major leakage - off mixture ratio	Propellant vapors/liquids in vehicle pod; potential fire	Machined bar stock, quality material; all EB welds, 100 percent inspected; cool operation	Visual inspection
Injector to Chamber Braze Confine hot combustion gases within chamber	External Joint Leakage	Minor Major	Performance loss with nonuniform cooling. Potential structural damage	Propellant vapors/liquids in vehicle pod; potential fire	Stress excursions within yield; structural integrity of joint demonstrated under vibration tests equilibrium to 100 MDC.	Chamber pressure visual inspection
Thrust Chamber Receive propellants under pressure; contain burning propellants.	Fails to impart high velocity to combustion gases to produce thrust	Critical	Throat erosion (if sufficiently severe, structural failure could occur.	No effect (Engine redundancy)	Single piece, all metal, durable, high strenght beryllium, thermal forgiving. INTEREGEN cooled walls. Demonstrated cool operation.	Condition monitored chamber pressure - pressure correlations
	External leakage	Critical to Catastrophic	Crack in engine wall	Combustion gases in vehicle pod: fire	Single piece, durable, high strength beryllium, INTEREGEN cooled walls; demonstrated cool operation	Chamber pressure visual inspection
Seal, Chamber to Nozzle	External leakage	Minor	No effect Redundant sealing	No effect	Clamp nut designed so adequate clamping force is maintained at all times without yielding material; used on MM '71 and VO '75.	Visual inspection
Nozzle Contained combusted gases and impart high velocity to expelled combustion gases to produce thrust	External leakage	Critical to Catastrophic	Failure of nozzle wall	Hot combustion gases in vehicle pod: fire	Single piece durable, high-strength columbium radiation-cooled walls; thermally insulated exterior proven Technology	Visual inspection

Maintainability. The beryllium RCS engine has been designed so that no servicing or periodic replacement would be necessary in the 100-flight, 10-year life span; however, fault detection/isolation instrumentation and visual inspection is recommended to monitor performance degradation for unscheduled maintenance. Time and resources required for corrective maintenance have been minimized by the use of condition monitoring. On-board equipment used in flight to monitor engine operational status, combined with visual inspection, will provide the primary indication for maintenance action. This rapid malfunction detection and isolation capability is augmented by engine design features that permit ease of maintenance.

PHASE II--HARDWARE FABRICATION

During this program, three test configurations were assembled from components purchased and fabricated under the contract or available from previous company-sponsored programs. The three test units were the Durability Engine, Off-Limits Engine, and Vibration Simulator.

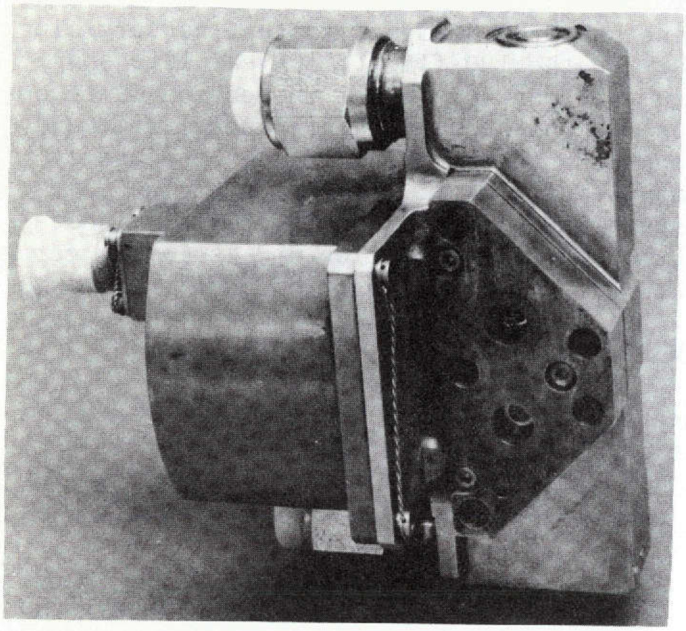
DURABILITY ENGINE FABRICATION

The Durability Engine Assembly is shown in Fig. 3 . The major engine components are shown in Fig. 11. The injector and columbium nozzle were supplied from a Rocketdyne company-sponsored program. The Moog valve model 54X107A was provided by NASA/JSC from Contract NAS9-12996. This valve failed during the test program and a second valve was provided.

The injector is an all-EB welded assembly with parent material between fuel and oxidizer manifolds. The orifices are EDM'd. Thrust chamber fabrication includes machining of the beryllium combustor, injector/chamber transition ring and nozzle nut; brazing the chamber and transition ring together; final machining the brazed transition ring; and EB welding on the nozzle nut and the injector to the chamber. The nozzles were fabricated by CS Industries. The columbium nozzles were coated locally by VacHyde (VH-101 silicide coating). The Dynaflex-insulation blanket was purchased from Johns-Manville.

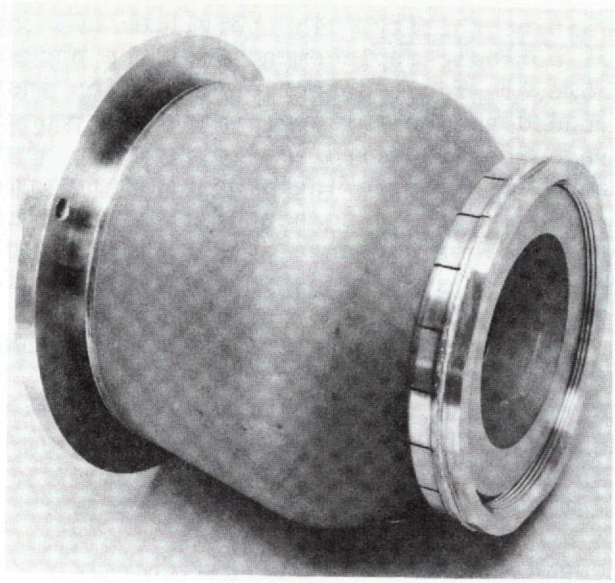
OFF-LIMITS ENGINE AND VIBRATION SIMULATOR FABRICATION

The Off-Limits Engine (Fig. 3) was available to the contract from a previous company-sponsored program. The Vibration Simulator assembly is also shown in Fig. 3. As previously discussed, the purpose of the simulator was to demonstrate the durability of the brazed joint. The injector/transition ring/beryllium combustor assembly was, therefore, identical to that employed in the durability engine. An aluminum cylinder was used for the nozzle that was clamped to the beryllium. A Moog valve, available from another Rocketdyne program whose mass is equivalent to that used on the Durability Engine, was bolted to the injector as a mass/center of gravity simulator.



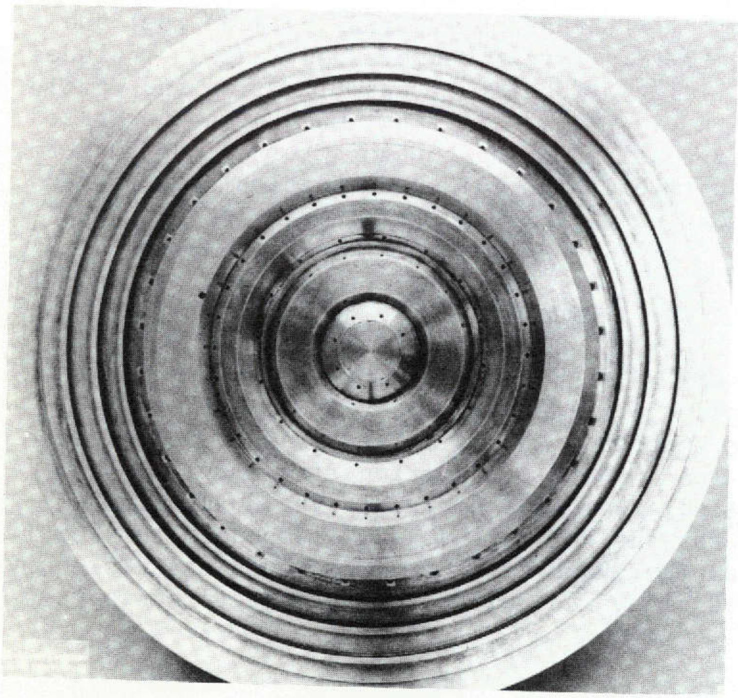
1SA22-12/14/73-C1H*

(a) VALVE



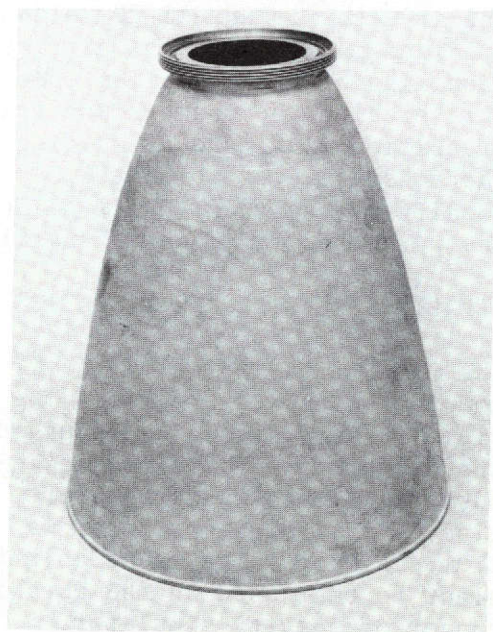
1SA22-12/14/73-C1G*

(b) COMBUSTION CHAMBER



5AD33-9/10/73-C1*

(c) INJECTOR



1XZ32-1/2/74-C1*

(d) NOZZLE

Figure 11. Durability Engine Components

PHASE III--ENGINE TESTING

During the test program, the Durability Engine was exposed to six environmental cycles interspersed with hot-fire tests where 500 starts and 1951 seconds were accumulated. The Off-Limits Engine was run at extreme mixture ratio and chamber pressure levels, as well as with plugged primary and auxiliary film coolant orifices. Eighteen starts and 2615 seconds were accumulated during contract tests. (Test hardware previously used on a company-sponsored test program has accumulated 694 starts and 6033 seconds.) The vibration simulator was exposed to 100 equivalent Space Shuttle missions of X, Y, and Z axis random vibrations.

DURABILITY ENGINE TEST PROGRAM

The Durability Engine was exposed to hot-fire and non-hot-fire environmental tests in the following sequence:

1. Acceptance hot-fire test
2. Baseline performance hot-fire test
3. First environmental test, sequence A
4. First hot-fire endurance test
5. Second environmental test, sequence A
6. Second hot-fire endurance test
7. Third environmental test, sequence A
8. Fourth environmental test, sequence B
9. Fifth environmental test, sequence B
10. Sixth environmental test, sequence B
11. Third hot-fire endurance test
12. Engine leak test and visual inspectioı

Table 5 presents the hot-fire test matrix. During the course of the test program, two Moog valves encountered excessive leakage problems. Throughout the above test sequence, the thrust chamber assembly was not decontaminated, even when servicing and installing valves.

TABLE 5. DURABILITY ENGINE TEST MATRIX

Sequence	Test No.	Test Dur.	Accum. Dur.	No. of Starts	Accum. Starts	Helium Sat.	Prop. Temp.	Mixture Ratio	Chamber Pressure
Acceptance Test	867	5	5	1	1	Yes	Ambient	1.55	197
	870	5	10	1	2			1.63	195
(Pulse train)	871-872	1.4	11.4	28	30			1.63	195
	873	100	111.4	1	31			1.63	194
Baseline Performance Test	45	10	121.4	1	32			1.56	194
	46	5	126.4	1	33			1.64	199
	52	600	726.4	1	34			1.66	190
(Pulse train)	53-68	30.65	760.05	130	164			1.62	179
Endurance Test No. 1	117	10	770.05	1	165			1.32	171
	118	5	775.05	1	166			1.34	174
	119	5	780.05	1	167			1.33	175
(Pulse train)	120-135	30.1	810.15	128	295			1.37	170
	136	5	815.15	1	296			1.34	179
	137	5	820.15	1	297			1.36	177
	138	5	825.15	1	298			1.50	178
	139	200	1025.15	1	299			1.58	184
Endurance Test No. 2	167	10	1035.15	1	300	No		1.46	191
	168	5	1040.15	1	301			1.82	208
	169	5	1045.15	1	302			1.65	198
(Pulse train)	170	139	1184.15	139	441			1.62	187
	171	200	1384.15	1	442			1.64	196
Endurance Test No. 3	296	10	1394.15	1	443	Yes		1.65	198
(Pulse Train)	297-353	57	1451.15	57	500			1.60	202

The acceptance test was conducted with ambient temperature and 100-percent helium-saturated propellants at simulated altitude. Testing consisted of two 5-second tests to verify thrust and mixture ratio were properly set; a series of 8 pulses, 50 msec on/1000 msec off; a series 20 pulses, 50 msec on/1000 msec off; and a 100-second burn.

The baseline performance test was conducted with ambient temperature and 100-percent, helium-saturated propellants at simulated altitude. Testing consisted of two calibration tests to verify thrust and target mixture ratio, the specified pulse sequence, and a 600-second, steady-state duration test. All non-firing environmental exposure tests were conducted at the Valley Division of AETL (Approved Engineering Test Laboratories).

The environmental tests were conducted according to MIL-STD-810B. Environmental sequence A involved exposing the engine to (1) rain, (2) humidity, (3) salt atmosphere, (4) sand and dust, and (5) vibration. Sequence B involved (1) rain, (2) sand and dust, and (3) vibration.

Two endurance tests were conducted per the test matrix of Table 5. The second endurance test was conducted with Marotta PV-20 facility valves. The Moog valve exhibited excessive leakage when attempting to initiate this test series and was, therefore, removed for failure analysis.

OFF-LIMITS ENGINE TEST PROGRAM

The Off-Limits Engine was hot-fire tested at simulated altitude with ambient temperature 100-percent saturated propellants per the matrix of Table 6. Test conditions were selected to simulate the off-limits operating capability of the engine. Specific objectives were to demonstrate:

1. Operation over a wide range of mixture ratio (1.45 to 1.85 o/f) and chamber pressure (150 to 230 psia)
2. Blowdown capability (reduce chamber pressure until pressure oscillations are excessive)
3. Simulation of a dual oxidizer regulator malfunction that can result in a mixture ratio of $\sim$3 o/f and chamber pressure of $\sim$235 psia
4. Operation with a plugged primary fuel orifice resulting in oxidizer impinging on the combustor wall causing localized high heat flux and an oxidizer-rich region
5. Operation with plugged film coolant orifices (one to four adjacent orifices) resulting in localized high heat flux regions

Eighteen tests were conducted, all at simulated altitude conditions. During the dual regulator malfunction simulation test the Haynes-25 nozzle extension reached equilibrium at 2300 F (Haynes-25 melts at approximately 2400 F). The resultant substantial loss in material strength resulted in nozzle damage. The nozzle was modified by removing the damaged section ($E_n \sim 7:1$) and the test program completed. This test established the limit for using Haynes-25 as a nozzle skirt material and

TABLE 6. OFF-LIMITS ENGINE TEST SUMMARY

TEST SERIES	TEST NO. 870-	TEST DURATION SEC.	DATA POINT DUR. SEC.	ACCUM. DUR. SEC.	MIXTURE RATIO, o/F	CHAMBER PRESSURE, PSIA
1. Oxidizer Regulator Failed Simulation	768	210	200	200	1.65	200
			10	210	2.88	237
2. Mixture Ratio/	781	884	150	360	1.65	200
			100	460	1.63	230
Chamber Pressure			100	560	1.44	229
Survey			100	660	1.43	200
			100	860	1.62	152
			100	960	1.83	202
			100	1060	1.82	230
			34	1094	2.04	184
	782	19	19	1113	1.90	153
	783	207	150	1263	1.66	201
			50	1313	1.86	201
			7	1320	1.96	184
	784	71	50	1370	1.65	201
			21	1391	2.04	202
	785	104	50	1441	1.67	201
			50	1491	2.01	230
			4	1495	2.12	223
	786	54	50	1545	1.65	201
			4	1549	2.39	216
	787	71	50	1599	1.65	201
			21	1620	1.99	160
Throttle Mode Operation	788	50	50	1670	1.67	152
	789	51	51	1721	1.69	128
	790	52	52	1773	1.70	102
	791	5	5	1778	1.58	66
	792	14	14	1792	2.08	204
3. Plugged Primary Fuel Hole	805	200	200	1992	1.68	202
4. One Plugged Coolant Hole	806	350	200	2192	1.59	201
			50	2242	1.79	153
			50	2292	1.83	153
			50	2342	1.81	179
5. Three Adjacent Plugged Coolant Holes	807	11	11	2353	1.65	201
	808	12	12	2365	1.64	201
	809	250	250	2615	1.64	200

resulted in the selection of a columbium nozzle for the Durability Engine tests. It is noted that the regulator malfunction test was repeated with a columbium nozzle during a company-sponsored program without incident (45-second test, nozzle reached equilibrium at 2300 F).

SIMULATED ENGINE TEST PROGRAM

The vibration simulator was subjected to 100 simulated random vibration space shuttle missions. One hundred minutes of random vibration had been completed in the X axis prior to a revision in the specification. The Y and Z axes were tested for 117 minutes each to the revised specification which reflects present shuttle orbiter launch levels. Posttest proof pressure at 500 psig and helium leak tests at 300 psig were performed after completion of the vibration testing.

PHASE IV--POSTTEST ANALYSIS AND DESIGN

Analyses of the Phase III test results is presented in this section along with a discussion of the impact of the test results on the projected flight configuration.

DURABILITY ENGINE TEST RESULTS

Steady-State Performance

The steady-state performance characteristics of the Durability Engine demonstrated throughout the test program are plotted in Fig. 12. A vacuum specific impulse of 290 and 294 lb_f-sec/lb_m was demonstrated at nominal conditions (200 psia chamber pressure, 1.63 o/f mixture ratio) for saturated and unsaturated propellants, respectively. An additional 1-second specific impulse could be obtained with an optimum 80 percent bell nozzle.

The engine pressure profile is shown in Table 7 as determined from the acceptance test data with the Moog, Inc., valve model 54X107A S/N 003. The profile is based on data taken at 100-second duration (test 873) at 194-psia chamber pressure with the valve inlet pressure on the oxidizer and fuel sides at 297 and 267 psia, respectively. At 200-psia chamber pressure, injector inlet pressures would be 246 and 250 psia such that in a flight configuration with a 30-psid valve and 10-psid calibration orifice, the engine inlet pressure requirement would be 290 psia.

TABLE 7. DURABILITY ENGINE PRESSURE PROFILE

	Fuel, psia		Oxidizer, psia	
	Test	Nominal	Test	Nominal
Valve Inlet Pressure	266.8	277.1	296.9	309.4
Valve Outlet Pressure	241.2	249.5	237.4	245.8
Injector Manifold Pressure	236.3	244.6	234.9	243.2
Injector End Chamber Pressure	195.5	201.1	195.5	201.1
Nozzle Stagnation Chamber Pressure	194.3	200.0	194.3	200.0

Pulse Performance

Figure 13 presents pulse performance measured during the baseline performance and endurance test series 1. Pulse data were not obtained during endurance tests 2 and 3 because of the use of facility valves in place of the malfunctioning Moog valve. Multiple 1-second pulses replaced the pulse sequence for these tests. The pulse data (Fig. 13) indicate the engine meets the pulse specific impulse goal of 220 lb_f-sec/lb_m at 30 lb_f-sec pulse total impulse at a pulse frequency of 5 cps. Since the injector design was constrained by existing facilities and valves, which necessitated a large manifold volume, the 220 lb_f-sec/lb_m goal could be met at lower pulse frequencies with a flight design.

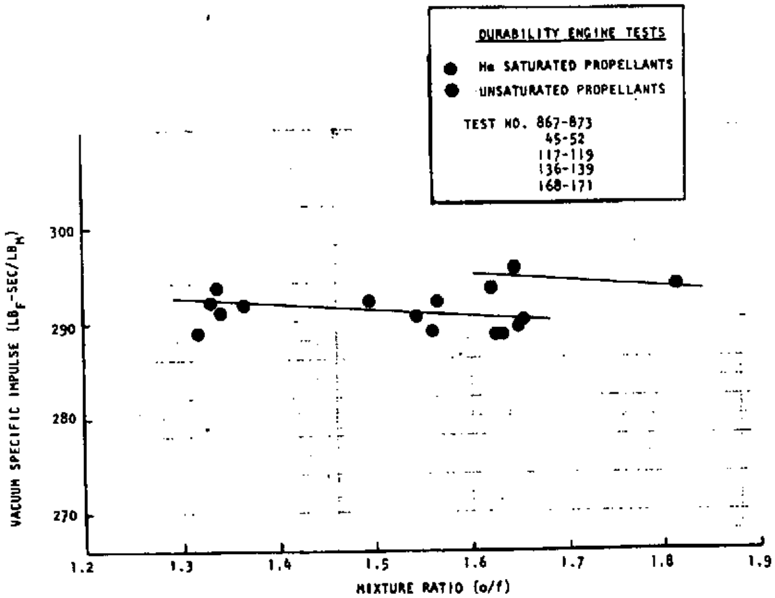


Figure 12. Durability Engine Steady-State Performance Specific Impulse vs Mixture Ratio, ϵ_N = 40:1

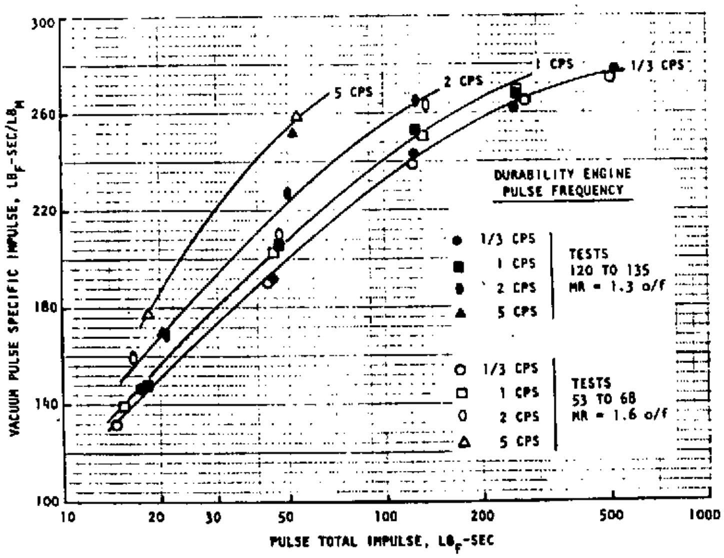


Figure 13. Durability Engine Pulse Performance Pulse Specific Impulse vs Pulse Total Impulse, ϵ_N = 40:1

Engine start times (valve signal to 90-percent thrust) of 40 msec were measured for 1/3 cps pulses and 30 msec for 5 cps pulses. Decreased start times with increased pulse frequency reflects the fact that the engine manifolds are not totally purged prior to each subsequent pulse. Cutoff time (valve signals to 10-percent thrust decay) of 20 msec were recorded.

Thermal Characteristics

The Durability Engine was tested with both an uninsulated Haynes-25 nozzle extension (acceptance tests) and an insulated (Johns-Manville Dynaflex) coated columbium (C-103) nozzle extension (all subsequent tests). At the conclusion of the 100-second acceptance test, the uninsulated Haynes-25 nozzle had reached a temperature of 1750 F. The beryllium at the injector end was at 190 F and at the throat was below 500 F. All temperatures, except the nozzle nut, had effectively reached thermal equilibrium conditions. Figure 14a provides temperature data for the 600-second baseline performance test performed with the insulated configuration. All temperatures reached equilibrium in 200 seconds of on-time. The recorded beryllium temperatures were relatively unchanged, 500 F at throat, from those measured during the test without the nozzle insulation blanket. The measured peak nozzle temperature was 2000 F. The insulation outside temperature exceeded the 800 F requirement by 75 F at the end of the test. This can be explained by the unoxidized condition of the titanium insulation blanket.

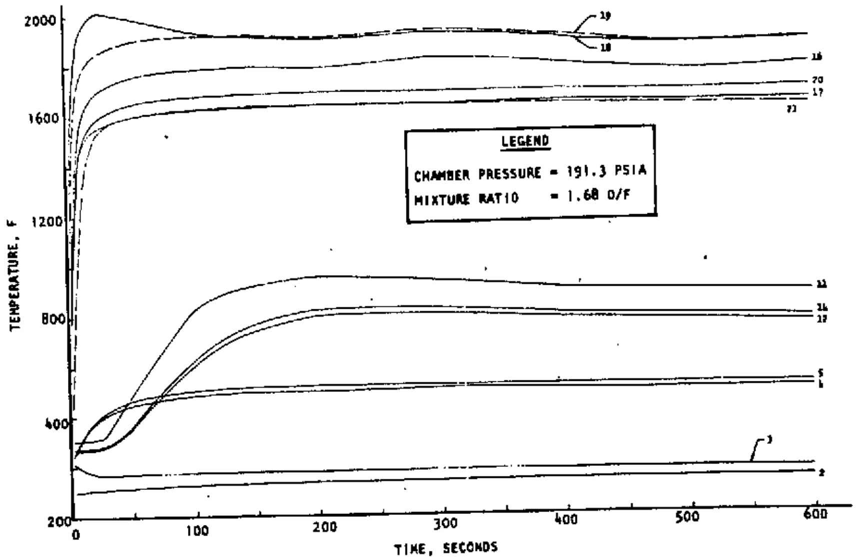
The data of endurance test No. 2 indicate a maximum nozzle temperature of 2000 F. The throat outside surface temperature of 600 F was recorded at 0-, 180-, and 270-degree angular locations. A throat outside surface temperature of 835 F was measured at a location of 90 degrees. Posttest inspection revealed four plugged film coolant holes at this location. The beryllium combustor head end temperature of 200 F was recorded on each side of the plugged film coolant region. Injector backside and valve adapter temperatures were nominal at 160 and 60 F, respectively.

The thermal soakout results of tests under vacuum conditions (Fig. 14b) indicate 500 F equilibration beryllium combustor temperature in approximately 200 seconds after engine cutoff. A facility valve adapter was installed. Therefore, no meaningful results were obtained for a valve soakout temperature. However, a peak valve temperature of 200 F was reached 30 minutes after engine cutoff of endurance test No. 1, which had three plugged BLC orifices due to soil and dust exposure.

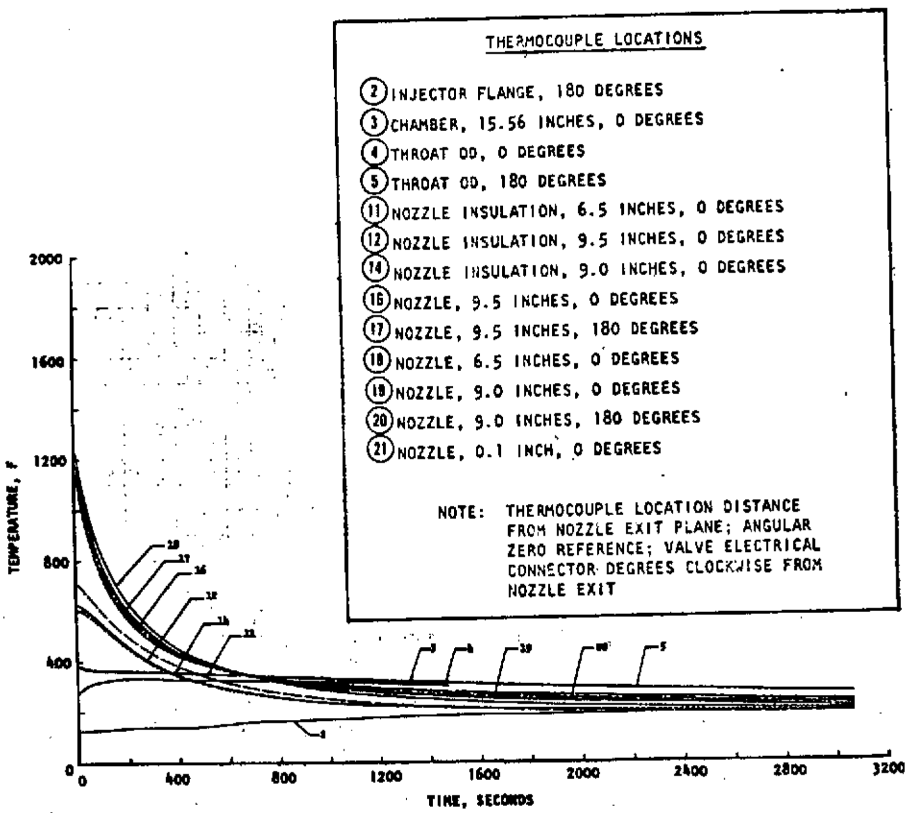
Throughout the test program, the recorded temperature data agreed with the theoretical predictions. The tests also demonstrated the ability of the engine to safely operate with multiple orifice plugging present due to environmental test conditions. Temperature levels are sufficiently low that further combustor optimization could result in engine weight reduction.

Environmental Tests

Excluding the propellant valve, the environmental tests had no adverse physical affect on the Durability Engine. Partial and total orifice blockage occurred due to sand and dust exposure on a wet engine from previous rain and humidity tests followed by vertical up and horizontal vibration. However, this did not



(a) Test 870-052, 23 January 1974



(b) Test 870-068 (Posttest Soak)

Figure 14. Temperature Versus Time, CTL-4, Cell 37

result in engine malfunctions though shifts in mixture ratio did occur during the first hot-fire test in each series subsequent to environmental exposure and high heat input was recorded where fuel film coolant orifices were plugged. Some superficial pitting was noted on the beryllium after salt spray exposure but this has no effect on engine operation or structural integrity.

Vibration Test Results. The Durability Engine was instrumental with accelerometers and strain gages and subjected in the three engine axes to sinusoidal and random vibration inputs. No detrimental effects on the engine were noted as a result of these vibration tests. Strain gage data indicated that low-frequency resonant modes were present in the 150 to 250 Hz frequency range. High frequency strain responses were noted, particularly in the 900 to 1500 Hz frequency range. The maximum strain amplitude was measured in the Haynes 25 transition ring (braze joint between injector and chamber). The joint is capable of inertial loads on the order of 5.7 times that measured (58 μ in/in rms) in the engine vibration test.

Propellant Valve Failures

Two Moog, Inc., Model 54X107A bipropellant valves were supplied to Rocketdyne to support the program. During the program, both valves exhibited failure modes. Both valves were fabricated using valve bodies from Model 103A used on the Minuteman III PBPS axial engine. The added flowrates required for a 600-pound-thrust engine were provided for by staggered seats, larger seat diameters and longer strokes.

Valve S/N 003 was supplied to Rocketdyne by NASA/JSC as residual hardware from NASA Contract NAS9-12996. Before delivery to Rocketdyne, the valve had undergone an extensive hot-fire and environmental test program. Gross oxidizer leakage was encountered through the valve after environmental testing at Rocketdyne. The manifold assembly was removed at Moog and visual inspection revealed the presence of gross amounts of fine textured sand. It was concluded that the sand, dust, and salt spray introduced into the engine nozzle during the environmental tests, migrated through the engine injector into the valve outlets during random vibration tests and abraded the oxidizer side Teflon seal.

Leakage on valve S/N 005 became increasingly worse as environmental testing progressed. This valve suffered the same failure mode experienced by S/N 003.

OFF-LIMITS ENGINE TEST RESULTS

Performance and Thermal Characteristics

Eighteen steady-state altitude tests were conducted with the Off-Limits Engine. A summary of performance and thermal data obtained during these tests is presented in Table 8. The tests consisted of demonstrating beryllium engine operation under extreme off-limit conditions; namely, simulated oxidizer regulator failure (2.88 o/f mixture ratio with 237 psia chamber pressure), mixture ratio

TABLE 8. OFF-LIMITS ENGINE TEST DATA

Date	Test No.	Total Duration, seconds	Data Point Duration	Mixture Ratio,* o/f	Chamber Pressure (NS), psia	Characteristic Velocity, ft/sec	Specific Impulse,** lbf-sec/lbm	Engine Temperatures, F		
								MID Chamber	Throat Maximum	Nozzle Maximum
11/6/73	768	210	200	1.65	200.2	4954	--	337	511	1770
			10	2.88	237.0	5001	--	352	601	2300
11/14/73	781	884	150	1.65	200.4	4983	283.4	320	539	1462
			100	1.63	229.9	4929	279.5	331	582	1473
			100	1.44	229.3	5049	286.0	331	586	1525
			100	1.43	199.7	5091	289.2	327	570	1536
			100	1.44	150.2	5114	292.2	295	444	1280
			100	1.62	152.3	5133	293.2	299	468	1402
			100	1.83	201.5	4958	281.3	328	582	1526
			100	1.81	229.5	4829	273.4	329	570	1413
			34	2.04	184.3	5201	293.8	340	693	2017
	782	19	19	1.90	153.4	5174	289.3	368	611	1907
11/16/73	783	207	150	1.66	200.5	4980	281.0	324	567	1661
			50	1.86	201.1	4964	280.0	332	619	1697
			7	1.96	184.0	5101	286.0	333	628	2025
	784	71	50	1.65	200.5	4990	281.8	329	557	1666
			21	2.04	202.4	5030	283.0	341	686	1847
	785	104	150	1.67	201.1	4997	282.4	332	559	1487
			50	2.01	230.2	4890	276.7	361	737	1719
			4	2.12	222.6	5011	282.5	364	744	1842
	786	54	50	1.67	200.8	4995	283.8	336	568	1494
			4	2.39	215.8	5141	291.2	335	569	1717
	787	71	50	1.65	201.1	5017	283.2	328	558	1476
			21	1.99	160.1	5260	293.7	326	598	1868
	788	50	50	1.67	151.8	5099	291.3	312	492	1425
	789	51	51	1.69	127.9	5231	--	296	470	1548
	790	52	52	1.70	101.5	5148	--	273	396	1707
	791	5	5	1.58	66.2	4532	--	278	299	748
	792	14	14	2.08	203.7	5062	283.9	290	485	1782
11/21/73	805	200	200	1.68	201.7	5043	284.7	377	605	1764
11/28/73	806	350	200	1.59	200.9	5117	288.5	363	568	1614
			50	1.79	152.7	5290	294.5	360	633	1900
			50	1.83	153.1	5298	295.4	399	742	1986
			50	1.81	178.5	5176	290.7	392	692	1831
11/29/73	807	11	11	1.65	200.5	5121	287.4	174	297	1969
	808	12	12	1.64	200.5	5103	286.6	258	384	2020
	809	250	280	1.64	200.2	5084	287.1	443	726	2211

*Percent of total flowrate
**Corrected to expansion ratio of 40:1

NOTES:

1. All tests conducted with propellants saturated with helium
2. All tests conducted with propellant temperatures within the ranges of 50 to 70 F
3. Facility valves used to conduct all tests

ranges of 1.43 through 2.88 o/f with throttling that resulted in chamber pressures of from 66 through 237 psia, and discrete tests with one plugged primary fuel hole (oxidizer stream sprayed directly on wall), one and three adjacent plugged coolant holes. The engine accumulated a total of 2615 seconds of burn time during the 18 starts.

The result of the chamber pressure/mixture ratio excursions defined engine operating regimes (Fig. 15). The data points describe an operating map where the engine can safely operate with a Haynes-25 nozzle extension. If actual SS/RCS operational requirements exceed this envelope, the beryllium engine will be able to meet these conditions by using a coated columbium nozzle extension. The Haynes-25 has a useful temperature limit of approximately 2100 F. Mixture ratio/chamber pressure conditions in excess of approximately 2.0/230 psia, 1.9/150 psia produce nozzle extension temperatures in excess of the useful limit of Haynes-25, which could result in nozzle extension damage.

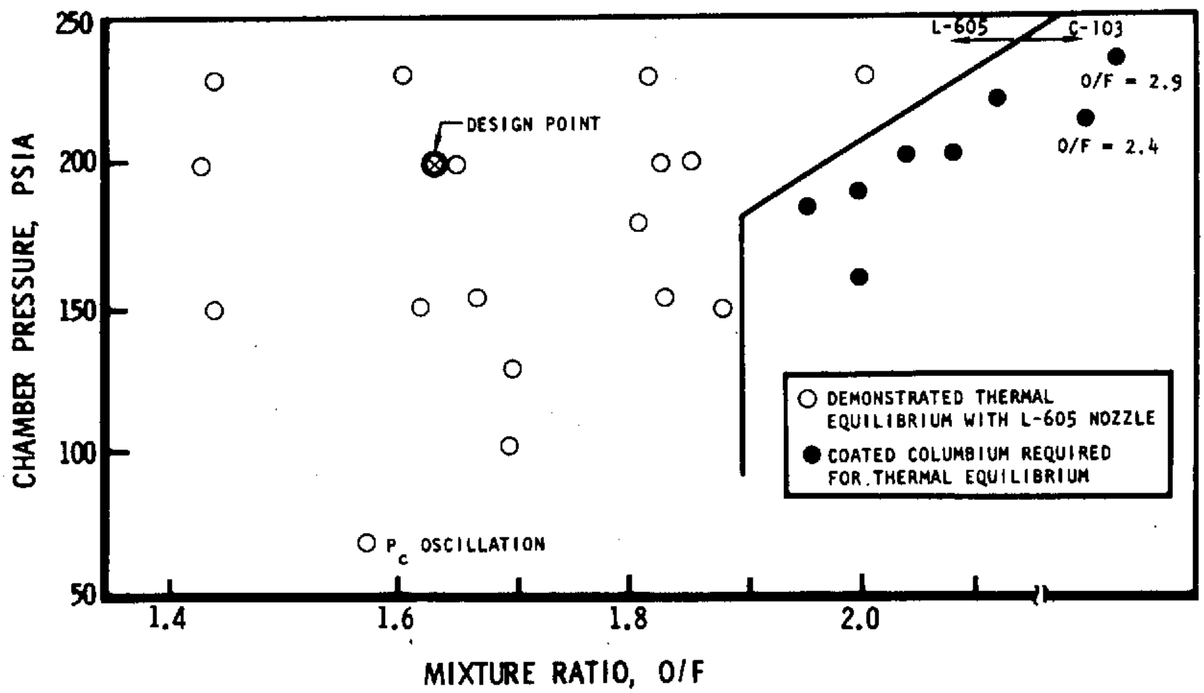


Figure 15. Demonstrated 600-Pound-Thrust SS/RCS Engine Operating Map

Five tests were conducted with various injector plugged orifice conditions. Test 805 was conducted with one primary fuel hole located adjacent to the chamber wall being plugged which resulted in the direct impingement of the oxidizer onto the beryllium chamber wall. Test 806 was conducted with one coolant hole being plugged. Test 807, 808, and 809 were conducted with three adjacent cooling holes being plugged. All temperatures reached thermal equilibrium during these tests. The beryllium chamber was in excellent condition after these tests, which correlates with the extremely low recorded hot streak temperature of 726 F. Under a company-sponsored program, a test was performed with four adjacent film coolant holes plugged and a columbium nozzle installed. The nozzle reached an equilibrium temperature below 2000 F.

Throttle mode tests were conducted with the engine operated from the nominal 200-psia chamber pressure through a low of 67-psia chamber pressure. Stable operation was achieved between 200- to 102-psia chamber pressure. Intermittent pressure oscillations at 110 Hz and magnitudes of ±15 psi were observed at the 102-psia level (50-percent throttle with helium saturated propellants). Chamber oscillations of ±40 psi were observed at the 67-psia operating level.

At the completion of the off-limits test program, the beryllium chamber was in excellent condition as was the chamber/nozzle extension joint and the nozzle extension section not damaged during the mixture ratio 2.9 o/f test.

VIBRATION SIMULATOR TEST RESULTS

The simulator was designed to evaluate the brazed joint of the engine and to obtain the same frequency response as the engine in the 20 to 2000 Hz frequency range by replacing the nozzle extension with an aluminum tube and using a dummy valve. Analysis of the strain gage data indicated that the primary resonant frequency of the simulator was a lateral bending mode at 150 to 200 Hz. A maximum strain amplitude of ~125 μ in./in. rms (350 μ in./in. peak) was measured. The injector/chamber braze joint was designed for a load that would result in 1000 μ in./in. peak strain. Therefore, the joint is designed to withstand inertial loads loads of approximately 2.5 times that measured in the test.

ENGINE DESIGN UPDATE

During this program, the ability of a beryllium INTEREGEN-cooled engine with a columbium nozzle to meet the severe operating requirements of the SS/RCS with large thermal margins was demonstrated through analysis and experimental programs. The problems encountered (valve failure and injector orifice plugging) are independent of the cooling process. Both these problems were associated with environmental exposure tests, more specifically exposure to large quantities of sand and dust with a wet engine before random vibration testing. Orifice plugging was demonstrated not to be a problem relative to safe engine function; however, mixture ratio shifts could occur that would affect propellant consumption. Since the largest injector hole in the injector was more susceptible than the smaller ones, reducing the number of elements does not appear to be a solution to obviating orifice plugging. The migration of particles to the valve could be a severe problem, however. Unless a valve is developed that does not degrade in the environment, the engine will have to be protected from sand and dust and/or purged before each mission.

The large thermal margin demonstrated on the engine indicates that substantial weight reduction could be made by reducing the mass of the beryllium. In addition, a lower contraction ratio configuration is feasible, which would result in both lower combustion chamber and injector weight.

A comparison of projected weight reduction with the Durability Engine configuration is shown in Table 9. As noted within this report, the Durability Engine injector weight was not optimized (designed to mate with existing valve and test facility, excess external material not machined to reduce fabrication cost). The weight of the two flight configurations reflect optimized injector weight with a flush-mounted valve and scalloped exterior. This weight reflects that of a two-piece thrust chamber where the nozzle extension is adaptable to any vehicle interface scarfing requirement.

TABLE 9. BERYLLIUM INTEREGEN ENGINE WEIGHT COMPARISON

	Test Configuration	Optimized Flight Configuration (ξ_c = 6)	Optimized Flight Configuration (ξ_c = 4)
Valve*	4.55	4.55	4.55
Injector	6.04	3.31	2.21
Combustor	3.86	3.33	2.62
Nozzle	2.81	2.81	2.81
Nozzle Nut	0.86	0.86	0.86
Total	19.00	15.74	13.93

*Mechanically linked, single-stage, bipropellant valve

CONCLUSIONS

The beryllium INTEREGEN engine has successfully completed a rigorous hot-fire and environmental test program. The results of testing have indicated that performance, thermal characteristics and durability are consistent with space shuttle application requirements. The following conclusions can be drawn from the test program:

1. The engine has demonstrated 294.4 lbf-sec/lbm steady-state specific impulse with unsaturated propellants at the nominal design point. Specific impulse is projected to 295.8 lbf-sec/lbm by incorporating an optimum nozzle contour. Further performance gains can be made by reduction in film coolant and adjustment in propellant outer row momentum angle.

2. The pulse specific impulse goal of 220 lbf-sec/lbm was demonstrated for a minimum impulse bit of 30 lbf-sec at a pulse frequency of 5 Hz. The pulse specific impulse goal can be met at lower pulse frequencies with reduced injector volumes. The propellant injection volumes were compromised by valve mounting configuration and the fact that downstream of the seat, valve volumes were large. Reconfiguration of the valve seating to reduce volume and design to allow valve mounting directly on the back face of the injector is recommended.

3. An engine start time of 0.040 second and cutoff time of 0.020 second was demonstrated with the MOOG inc. valve.

4. Chamber pressure overshoot associated with start transient was a maximum of 20 percent which is no compromise to engine life or performance.

5. The engine demonstrated very broad off-limits operation capability (1.43 to 2.88 o/f mixture ratio and 66 through 230 psia chamber pressure) without sustaining damage. However, the worst case simulated dual oxidizer regulator failure (2.88 o/f mixture ratio with 237 psia chamber pressure) mode of operation, high temperatures in the Haynes 25 nozzle extension caused a failure of the material. This test was repeated successfully with this engine with a columbium nozzle extension on a company sponsored program. Discrete tests with one plugged primary fuel hole and one and three-adjacent plugged coolant holes were conducted to steady state at nominal conditions with the Off-Limits Engine. The engine throat outside surface temperatures reached predictable values which demonstrated the feasibility of reliable engine shutdown devices to allow for subsequent engine operation. The plugged coolant orifices caused only slight oxidation of the throat ID downstream of the plugging.

6. At nominal operating conditions (200 psia chamber pressure, 1.63 o/f mixture ratio) with a 30 psid valve and allowing 10 psid calibration orifice, the inlet pressure is 290 psia which meets the design requirement.

7. The maximum single burn requirement of 600 seconds was demonstrated with steady-state performance and thermal equilibrium conditions achieved. Lower than steady-state mean operating temperatures were demonstrated for pulse operation over a pulse frequency range of from 1/3 to 5 Hz with pulse widths of 0.050 to 1.0 second with no degradation to performance or engine integrity.

8. Thermal equilibrium was demonstrated: with and without a nozzle extension insulation blanket, with and without helium saturated propellants, with one primary fuel hole plugged (oxidizer on wall), with one coolant hole plugged and with four adjacent coolant holes plugged.

9. High cycle life capability was demonstrated by the attainment of low beryllium chamber operating temperatures and thermal gradients. The low operating temperatures at nominal conditions provided large thermal margin which allows for operation over a wide range of inlet conditions.

10. The valve seat maximum soakout temperature from engine operation was well within limits to allow for engine restart and not impose restrictions on life or performance.

11. The nozzle extension thermal insulation exceeded the maximum specified temperature requirement of 800 F by approximately 75 F. However, the external titanium shell can be painted with emissivity control paint or a slight increase in Dynaflex blanket thickness will provide the required effect with better reliability.

12. The Durability Engine while subjected to six environmental cycles did not encounter adverse effects other than slight superficial staining and minor pitting of the beryllium chamber. The engine successfully completed the sinusoidal vibration testing with no evidence of detrimental effects. During random vibration testing, strain gage data indicated that low frequency resonant modes were present in the 150 to 250 Hz frequency range. Strain values recorded in the braze transition joint between the injector and chamber were on the order of one half that allowed for in the design. Therefore, the design is capable of withstanding inertial loads greater than twice those experienced in test.

13. The Vibration Simulator demonstrated successful completion of random vibration test equivalent to 100 space shuttle missions. The measured peak strain amplitude was less than one-half the design value. Therefore, the injector/chamber braze joint was designed to withstand inertial loads greater than those experienced in test.

14. The MOOG Inc. bipropellant valve was used for acceptance and baseline performance testing. Due to its inlet pressure limitations and marginal operating characteristics, facility valves were required for the off-limits testing. Also, severe damage was sustained by the valve seats

during environmental testing due to migration of sand/dust particles between the poppet and seat during vibration sequence even under specification lockup inlet pressures. It is obvious from this testing that redesign of the valve seat is required and/or precautions must be taken to preclude the admittance of sand and dust into the engine whenever possible. The precautions could be taken in the form of inexpensive blow out throat plugs or nozzle exit covers.

15. Posttest analyses indicate that lower weight designs are feasible by recontouring the beryllium chamber and scalloping the injector. Also, additional weight reductions are possible by incorporating designs of lower contraction ratio. Thermal predictions using correlations with test data acquired in this program indicate adequate cooling is available to effect the lower contraction ratio designs.

16. The results of this program suggest that the beryllium INTEREGEN cooling concept is capable of application to higher thrust and chamber pressure regimes.